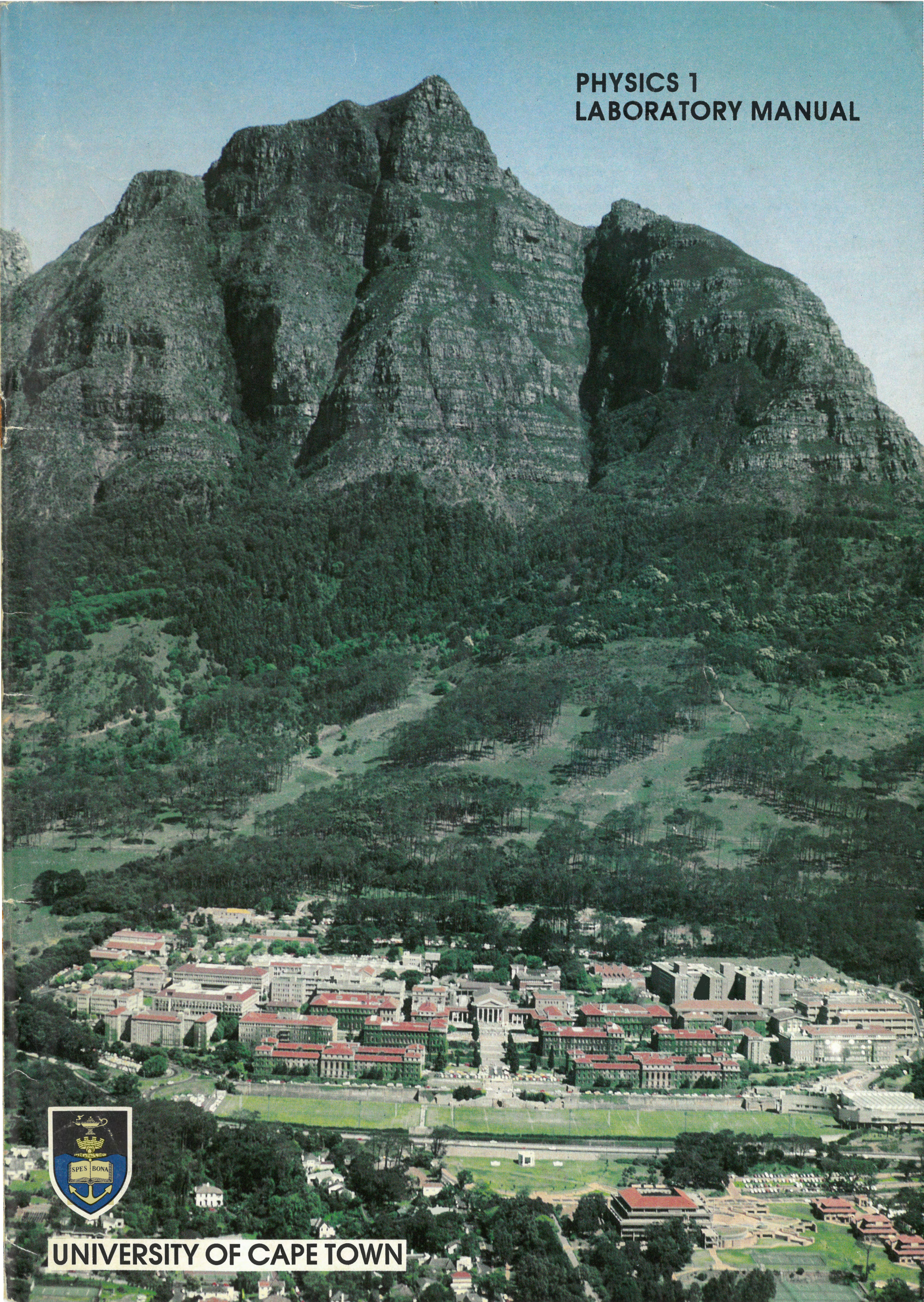
PHYSICS 1
LABORATORY MANUAL



UNIVERSITY OF CAPE TOWN

B

Lab Wk	DATES	PHY100W (Grp 1 & 2)	PHY104W (Grp 3 & 4)	PHY110W (Grp 5 & 6)	PHY110W (Grp 7 & 8)
1	Tues 27 Feb ➡ Mon 4 Mar	Introductory	Lecture &	Exp 1 (Hooke's	Law)
	Tuesday 5 March	*SAX*	*APPEAL*	*DAY*	*HOLIDAY*
2	Wed 6 Mar ➡ Tues 12 Mar	Tut 1	Exp 2 (Uncert)	Exp 6 (Free Fall)	Exp 2 (Uncert)
3	Wed 13 Mar ➡ Tues 19 Mar	Exp 7 (Newton)	Exp 6 (Free Fall)	Exp 2 (Uncert)	Exp 6 (Free Fall)
	Wednesday 20 March	*BYE DAY*	*NO*	*LABS*	---
	Thursday 21 March	*HUMAN*	*RIGHTS*	*DAY*	*HOLIDAY*
4	Fri 22 Mar ➡ Thur 28 Mar	Exp 6 (Free Fall)	Tut 1	Tut 1	Tut 1
5	Fri 29 Mar ➡ Thur 4 Apr	Tut 2	Exp 7 (Newton)	Exp 3 ** (Pend)	Exp 7 (Newton)
	Friday 5 April	*GOOD*	*FRIDAY*	—	----
		MID -- TERM.	*VACATION*	*Sat 6 ➡ Sun 14*	*APRIL*
6	Mon 15 Apr ➡ Fri 19 Apr	Exp 2 **(Uncer)	Exp 3 ** (Pend)	Exp 7 (Newton)	Exp 3 ** (Pend)
7	Mon 22 Apr ➡ Fri 26 Apr	Exp 3 (Pend)	Tut 2	Tut 2	Tut 2
8	Mon 29 Apr ➡ Fri 3 May	Tut 3	Exp 8 (Rot Dyn)	Exp 9 (S H M)	Exp 8 (Rot Dyn)
	Wednesday 1 May	*WORKERS*	*DAY*	*Alternative*	*arrangements.*
9	Mon 6 May ➡ Fri 10 May	Exp 14 (Gas L)	Exp 9 (SHM)	Exp 8 (Rot Dyn)	Exp 9 (SHM)
10	Mon 13 May ➡ Fri 17 May	Exp 13 **(Visco)	Tut 3	Tut 3	Tut 3
11	Mon 20 May ➡ Fri 24 May	Tut 4	Exp 14 **(Gas L)	Exp 13 ** (Visco)	Exp 14 ** (Gas L)
12	Mon 27 May ➡ Fri 31 May	Lab Exam	Lab Exam	Lab Exam	Lab Exam
		STUDY	*WEEK*	*3 ➡ 7 June*	
		EXAM	*PERIOD*	*10 ➡ 28 June*	
		MID -- YEAR	*VACATION*	*29 JUNE ➡*	*21 JULY*
13	Mon 22 July ➡ Fri 26 July	Exp 8 (SHM)	Exp 18 (Multim)	Tut 4	Tut 4
14	Mon 29 July ➡ Fri 2 Aug	Exp 18 (Multim)	Tut 4	Exp 14 (Gas L)	Exp 13 (Visco)
15	Mon 5 Aug ➡ Fri 9 Aug	Tut 5	Exp 17 (Oscillo)	Exp 16 (Ohm)	Exp 18 (Multim)
16	Mon 12 Aug ➡ Fri 16 Aug	Exp 16**(Ohm)	Exp 19**(Elec H)	Tut 5	Tut 5
17	Mon 19 Aug ➡ Fri 23 Aug	Exp 17 (Oscillo)	Tut 5	Exp 18 (Multim)	Exp 16 **(Ohm)
18	Mon 26 Aug ➡ Fri 30 Aug	Tut 6	Exp 20 (LCR Res)	Exp 19**(Elec H)	Exp 17 (Oscillo)
19	Mon 2 Sept ➡ Fri 6 Sept	Exp 4 (Lenses)	Exp 10 (Vib Str)	Tut 6	Tut 6
		MID -- TERM.	*VACATION*	*Sat 7 ➡ Sun 15*	*SEPTEMBER*
20	Mon 16 Sept ➡ Fri 20 Sept	Exp 10**(Vib Str)	Tut 6	Exp 17 (Oscillo)	Exp 19 (Elec H)
21	Mon 23 Sept ➡ Fri 27 Sept	Tut 7	Exp 12 (Coup Osc)	Exp 20 (LCR Res)	Exp 10 **(Vib Str)
	Tuesday 24 September	*HERITAGE*	*DAY*	*Alternative.*	*arrangements*
22	Mon 30 Sept ➡ Fri 4 Oct	Exp 21 (Na Spect)	Exp 22**(Rad Sh)	Tut 7	Tut 7
23	Mon 7 Oct ➡ Fri 11 Oct	Tut 8	Tut 7	Exp 10**(Vib Str)	Exp 20 (LCR Res)
24	Mon 14 Oct ➡ Fri 18 Oct	Lab Exam	Lab Exam	Lab Exam	Lab Exam
		STUDY	*WEEK*	*21 ➡ 25 October*	
		EXAM	*PERIOD*	*28 Oct ➡ 15 Nov*	

** ⇨ Long write-up.

NAME: ....

CLASS: B ....

DAY: THURSDAY ....

GROUP: ....

L-1-C : Prof Brookes

Lab attendant : Mr Chrishams

Co-ordinator : Dr D. Ball
Rm 505

Physics I
Laboratory Manual
1996

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Contents

Introduction

The laws of physics have been developed through the years by analysing measurements and observations of physical phenomena. The First Year Laboratory aims to further your knowledge and understanding of these laws with hands on practical experience. Your knowledge thus becomes first hand! Remember that each experiment aims to illustrate or apply some particular law or technique of Physics.

The laboratory has other objectives as well. These include the development of manipulative skills with apparatus; learning the purpose of and how to use specialised apparatus; and developing the *"scientific method"* of taking measurements, recording the data, setting out the calculations, analysing the results and drawing appropriate conclusions with reference to the laws of Physics.

The laboratory course complements and supplements the lecture material. Most of the theory appropriate to the experiments will be covered in lectures. However, it is not possible to fully coordinate laboratory and lecture topics, and you may well meet subject matter in the laboratory which has not yet been dealt with in lectures. It is thus imperative that you study IN ADVANCE the laboratory manual and any notes or references you may need in order to understand the basics of an experiment before you perform it.

1. **Laboratory and Tutorial Time**

   The *"laboratory afternoon"* is divided between experiments and tutorials in the ratio 2 : 1. The details of this allocation will depend on your lecture course (i.e. 100W, 104W, 110a, 110b) and are listed in the calendar on the inside cover of this manual.

2. **Laboratory Organisation**

   In the laboratory students work in pairs. On your first laboratory afternoon you will be asked to find a partner who is doing the SAME LECTURE COURSE. Give your names to the laboratory attendant on the slip provided.

   From the student pairs, groups of students are formed. Once you have found a partner you will be allocated to a group. The group lists will be posted before your second laboratory afternoon. Ensure that you know your GROUP NUMBER, as all your laboratory and tutorial activities are governed by this group number.

   The laboratory space is divided into "areas", each of which can accommodate 60 students. Each area will be controlled by a demonstrator who will be a member of staff or a postgraduate student. The demonstrator is responsible for the administration of the 60 students in his area (i.e. allocation of apparatus, marking of books, entry of marks, etc.) and will be assisted by another demonstrator. On your second laboratory afternoon, go directly to the laboratory area assigned to your group for that afternoon. You will then be assigned a set of apparatus.

   For each experiment, a short pre-prac talk will be given by the demonstrator to explain certain aspects of the experiment. Since these talks begin before the apparatus is assigned, it is important that students arrive promptly at 1.40 p.m. Each experiment must be completed and a report fully written up and marked or handed in during one afternoon in the laboratory.

3. **Laboratory Rules**

   (i) The laboratory is opened at 1.40 p.m. Experiments are expected to run from 1.40 to 4.30 p.m. The laboratory will remain open until 5.00 p.m. You are expected to attend until 4.30 p.m. each day. Only if you have completed the experiment assigned for the day, completed the report and had it marked are you free to leave before this time. Sports meetings and other social activities will NOT be regarded as sufficient reason for leaving early.

   (ii) You should work neatly, quickly and quietly.

   (iii) Certain apparatus such as stop-watches, thermometers, glass prisms, lenses, etc. will not be laid out on the tables. These items should be collected from the demonstrator or the laboratory attendant, and will be supplied to you in exchange for your registration card. Your card will be returned when you return the equipment.

(iv) If apparatus is missing from a set you are using or are about to use, DO NOT remove apparatus from another set. Ask the demonstrator for the missing apparatus.

(v) All apparatus should be handled with care. If you think your set is not working properly, ask your demonstrator to check it for you.

(vi) Accidents happen in even the best-regulated laboratories. If you should accidentally damage some apparatus, report the fact immediately to the lecturer- in-charge. No action will be taken against students who have genuine accidents. If the accident is due to carelessness, the responsible party will be charged for repair or replacement of the damaged apparatus.

(vii) Smoking is NOT allowed in the laboratory.

4. **Laboratory Record Book**

Experimental work, however well executed, will be of no value unless properly recorded. Learning the correct way to record experimental data, and presenting experimental findings therefore forms an essential part of your laboratory training. Your record of each experiment should be written in the blue book provided and should include:

(a) a title, date, the experiment number and particulars which will identify the equipment used (e.g. the set number);

(b) records of all readings taken, which should be neatly presented in well-planned tables;

(c) records of all calculations, including working; tabulated whenever possible;

(d) graphs clearly labelled and including calculation of the slope.

(e) clear statements of all results obtained and conclusions reached;

(f) discussions of errors and difficulties encountered.

You are not expected to copy out or paraphrase the instructions and notes which you will find in this manual. Your record should complement, extend and answer

what you find in the manual. Long after completing the experiment you should be able to recall and recount what you experienced and learned in doing so, simply by referring to your record book in conjunction with this laboratory manual. You will find this helpful, if not essential, in preparing for the laboratory examinations in June and October.

It is left to you to decide on a detailed form in which to lay out your laboratory records. However, your arrangement must satisfy the requirements stated in (a)-(f) above. Demonstrators will be ready to advise you when asked and to criticise when they check your records after each experiment. Some examples of model layouts will be provided in the first few laboratory afternoons to give you some ideas. After this it will be entirely your own responsibility to see that your records and results are properly arranged and presented.

5. **Laboratory Assessment**

Once you have completed your experiment each afternoon, you must present your record book to your demonstrator for marking. He (or she) will award a mark out of 5 or 10 (see Section 6) based on the quality and organisation of your write-up and the quality of the final result. This mark will count towards your laboratory record which, in turn, counts 5% towards your final mark for the year.

A further 20% of your final mark will come from the two laboratory examinations. Thus laboratory work counts a total of 25% towards your final Physics mark. To summarise this breakdown:

Laboratory record	5%
Laboratory exam #1 (June)	10%
Laboratory exam #2 (October)	10%

6. **Laboratory Write-up**

This year there will be two types of write-up:

(a) Shortened write-up

(b) Full write-up - indicated with *** on the calendar.

The shortened write-up requires only the data, calculations, graph, results and conclusions. No description of method or apparatus is required. Demonstrators will look at your work as you go along. At the end of the afternoon the demonstrator will complete his assessment of your work and award a mark out of 10.

Four times in the year you will be asked to complete a FULL write-up, as will be expected for the laboratory exams. This will have in addition a description in your own words of the apparatus and the experimental method you followed in doing the experiment. Extra care is expected to be taken with this presentation, and it will be handed-in for marking out of 20.

7. **What you will need in the Laboratory**

Certain things should be brought with you to every laboratory session. These include your UCT registration card, this manual, your record book, suitable stationery and a calculator. Your calculator should be able to perform all arithmetic and trigonometric functions, logarithms and exponentials. A last word about calculator use: you will doubtless find it a useful and time-saving tool in the laboratory, but take care to examine all calculated results to ensure that they are REASONABLE before recording them. For example, if you calculate the mass of an object to be 5.2×10^{24} kg, it might be wise to examine the calculation more closely!

In addition to these necessities, you may find it useful (and essential for some experiments) to bring geometrical instruments, particularly a protractor. Also, you may like to bring lecture notes or references if you think they will prove useful.

8. **Tutorial Organisation**

Tutorials are interspersed with the experiments, one every three weeks, as detailed on the calendar. The experiment- tutorial system is staggered, so that some students are in the laboratory, while others are doing tutorials. Here it is *vital* to know your group number, since tutorials are also arranged according to these groups. Be sure to consult the Physics Laboratory Noticeboard regularly for information about tutorials and experiments.

Each group of students is assigned a tutor for the tutorial sessions, which run from 1.40 p.m. to 3.30 p.m. It is important that you make the best possible use of the time allowed by asking questions.

On entering the tutorial room, students will be assigned to groups of three and supplied with four or five problem to be completed during the tutorial session. You are encouraged to discuss the problems with the members of your group. If your group is unable to solve a problem ask the tutor for assistance. By the end of the tutorial session students must know how to solve all the assigned problems and have a neat set of solutions. On showing your set of solutions to the tutor they will indicate in the register that you have completed the tutorial and you are then free to leave. Tutorial sessions may also be used to clear up any difficulties you may be having with the lecture material.

9. **Laboratory Examinations**

During the course of the year you will be required to perform two laboratory examinations, one in June and the other in October. The aim of these examinations is to test skill and judgement in carrying out a simple experiment. All students will perform the same experiment, but each will work alone. The experiment will not be one already performed during the year, but will rely on the same skills and techniques learned in the First Year Laboratory.

The examination question paper will be published on departmental noticeboards at least one week before the examination takes place, and a sample set of the apparatus to be used will be on display in the laboratory beforehand. Students

will thus be expected to arrive suitably prepared for the examinations.

10. **Laboratory and Tutorial D.P. Certificates**

The laboratory marks and tutorial symbols are important in the award of a DP certificate. Students who do not have satisfactory marks during the year, (60% for the lab. record) and/or who are absent without adequate excuse from three or more practical and/or tutorial classes, may be refused a DP certificate. If you are absent from an afternoon class owing to illness or for some other good reason, inform the lecturer-in-charge of your practical class; he/she will arrange for you to make up the work you have missed or excuse you from the practicals concerned.

Measurement and Significant Figures

No measurement can be perfectly accurate; there will always be some uncertainty attached to a measured value. Strictly, every measured value should be quoted together with a numerical uncertainty (or "error estimate"). Although you may often find this tedious, it is an essential part of the work of experimental physicists, and this laboratory course should give you much practice in estimating and working with uncertainties.

1. **Measurement**

As a golden rule, whenever you take a direct measurement, your result should be stated to the number of figures *as determined by the accuracy of your instruments.* For instance, when using a metre rule to measure distance, it may be possible (with care) to take a reading down to one tenth of a millimetre. Thus such a reading should be quoted as 121.7 mm but not 121.743 mm. Similarly, a reading of 8.0 mm is not the same as a reading of 8 mm. If you write 8 mm you imply that you did not attempt to read to better than the nearest millimeter. If you write 8.0 mm you imply that you *did* attempt to estimate to one tenth of a millimetre. You should always record your readings so that they correctly reflect the accuracy to which you attempted to work.

2. **Significant Figures**

The number of "useful" figures in a reading or a calculated value is known as the number of "significant figures" and is useful in giving a general idea of the accuracy of the number thus quoted. Some examples follow.

(a) AB = 25.1 cm means: the measured value of AB is 25.1 cm, correct to the nearest tenth of a centimetre. There are three significant figures in this number. On the other hand, AB = 25.10 cm means that the measured value of AB is 25.10 cm determined to the nearest hundredth of a centimetre. Here we have four significant figures. In the first case we understand that the true value of AB lies between 25.05 and 25.15; in the second case the value of AB is understood to lie between 25.095 and 25.105 cm.

(b) Zeroes that are used to place the decimal point are never significant. Thus 0.0121 has three significant figures, as can easily be seen if we write it as 1.21×10^{-2}.

(c) Physics uses many terms that are also used (much less exactly) in everyday life. Thus a statement in a newspaper article that "The baby elephant weighs 1500 kg" could have various implied accuracies:

(i) a guess by the zookeeper, say $\pm$ 100 kg

(ii) perhaps it was weighed on a weighbridge accurate to 10 kg

(iii) perhaps it was weighed on a balance accurate to 1 kg.

For scientific work we should write, for each of the above cases:

(i) 1.5×10^3 kg

(ii) 1.50×10^3 kg

(iii) 1.500×10^3 kg

and we would interpret these as follows:

(i) the elephant's mass is between 1.45 and 1.55×10^3 kg.

(ii) the elephant's mass is between 1.495 and 1.505×10^3 kg.

(iii) the elephant's mass is between 1.4995 and 1.5005×10^3 kg.

Again it should be stressed that in a direct measurement, the number of significant figures is determined *only* by the accuracy of the instrument (and the ability of the observer to use it).

However, often we need to use one or more direct measurements to *calculate* other quantities. For instance, we may measure the speed of a moving object and the distance it covers and wish to calculate the length of time for which it was in motion. How then do we decide how to quote our answer? This depends on whether we are adding the quantities concerned to arrive at our answer, or multiplying them, or using various combinations of these operations (or others).

Addition: (or subtraction) Here we examine the *absolute accuracy* (i.e. number of decimal places) in the quantities we have.

For example, suppose we have a car of total mass M = 1000 kg, measured on a balance with an accuracy of 2 kg. Then m = 1000 $\pm$ 1 kg. If a passenger of mass m = 80.35 kg gets into the car, what is the total mass of the vehicle now?

$$\begin{array}{lcrcl} \mathrm{M} & = & 1.000 & \times & 10^3\ \mathrm{kg} \\ \mathrm{m} & = & 0.08035 & \times & 10^3\ \mathrm{kg} \\ \hline \mathrm{Sum} & = & 1.080 & \times & 10^3\ \mathrm{kg} \\ \hline \end{array}$$

Note that the accuracy of the result cannot be better than the accuracy of the *least* accurate measurement involved. If we had written the sum 1.08035×10^3 kg, the last two figures would not be significant, since they are being added to an unknown quantity in the value for M.

Multiplication: (or division) Suppose we measure the sides of a rectangle and find them to be 10.2 cm and 15.6 cm. Then the area of the rectangle is

$$10.2 \times 15.6 = 159.12\ \mathrm{cm}^2$$

But are all five figures of the answer significant? Can we multiply two numbers of three-significant-figure accuracy to obtain an answer of five-significant-figure accuracy?

We have seen that 10.2 means "between 10.15 and 10.25"; 15.16 means "between 15.55 and 15.65". Thus the answer lies between $10.15 \times 15.55 = 157.8325$ cm^2 (smallest possible) and $10.25 \times 15.65 = 160.4125$ cm^2 (largest possible).

We see immediately that all the figures to the right of the decimal point are not significant: the figure 159 cm^2 suggests that the answer lies between 158.5 and 159.5. Thus two numbers each of three-significant-figure accuracy give an answer only to three-significant-figure accuracy.

Similar rough calculations show that, when multiplying two numbers of different accuracies, the result should normally be quoted with the number of significant figures of the *least* accurate number.

Rounding off. You will thus often need to round off your calculations to the correct number of significant figures (beware of calculators on this score!). The general rules for round off are as follows:

(i) The last significant figure to be retained remains unaltered if the next digit is less than 5. For instance, 3.434 rounds off to 3.43.

(ii) The last significant figure to be retained is increased by one if the next digit is more than 5. For instance, 3.436 rounds off to 3.44

(iii) If the next digit is a 5, you may choose either of the above.

NOTE: Do not do a double round off. 3.4348 rounded off to three significant figures becomes 3.43. Do *not* say 3.4348 → 3.435 → 3.44!

3. **Conventions**

In this manual the decimal point is denoted by a point '.' rather than a comma ','. We prefer this convention because it avoids confusion when we work with computers. However, it is not obligatory for you. It is also suggested that you use S.I. units throughout, as this will often simplify calculations and avoid errors.

A final word on the use of pencil in your record book: Pencils should be used for all diagrams, lines in tables, etc., but should not be used to fill in values or to write with. Your record book is not expected to be a work of art. Keep it as neat as possible, but measurements and calculations should be done *directly* into it, in pen, and mistakes should be neatly crossed out.

Data Analysis

1. **Graphs**

In Physics a measurement yields directly, or can be used to calculate, a physical quantity (e.g. time; distance; speed). We find that a particular physical quantity (e.g. distance) will usually depend on another quantity (e.g. time), and the first quantity is called "the dependent variable" and the second "the independent variable". We often label the dependent variable "y" and the independent variable "x", and write the dependent variable as a function of the independent variable, $y = f(x)$.

The variation of y with x is best illustrated by plotting a graph of y against x, since this presents a compact, easily assimilated summary of the data and its variation. If the variables plotted are intelligently chosen, the resulting graph may reveal not only the existence of a relationship between them, but also the form of that relationship, and thus the values of the parameters describing the relationship may be simply determined. These parameters are usually of physical interest.

No matter how closely a physical process is modelled by theory, there will always be some discrepancy between the data collected and the theoretical relationship. Thus, given a set of data, suspected to obey a particular relationship the data points must be plotted first and then the expected curve fitted to them as best possible. Only then can the parameters be determined from positions on the curve (not from data points). In plotting the graph certain conventions are rigidly followed, i.e.:

1) The axes of the graph are perpendicular. 2) The dependent variable is plotted along the vertical axis, increasing upwards. 3) The independent variable is plotted along the horizontal axis, increasing to the right. 4) The points are plotted as x or $\odot$.

1.1 Linear functions A linear function y of x has the form:

$$y = mx + c \qquad (0.1)$$

where m and c are constant parameters which, given any two distinct points, (x_1, y_1) and (x_2, y_2) say, can be determined by

$$m = (y_2 - y_1)/(x_2 - x_1) \tag{0.2}$$

$$\begin{aligned} c &= y - mx \\ &= y - [(y_2 - y_1)/(x_2 - x_1)]\,x \qquad (0.3) \\ &= y \text{ when } x = 0 \end{aligned}$$

A linear function has a straight line graph, with slope m, through y-intercept c, as shown in Fig. 0-1 below.

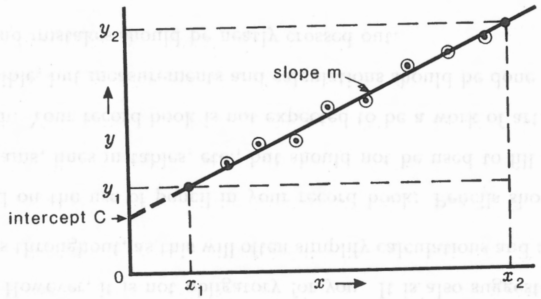


Fig.0-1

A linear function between two variables, with its straight line graph, is the commonest and simplest form to plot. Further, only two constants need be found, both of which are easily and accurately determined from the graph.

1.2 Non-linear functions

There are many non-linear forms relating two variables (e.g. $y = ax^2$; $y = ax + bx + c$; $y = \sin x$; $y = \exp x$; $y = \log x$). It is usually not possible to state, just by looking at a graph of a non-linear function y of x, which relationship holds or what parameter values are involved. Thus, when faced with a non-linear function, we usually try to recast it into a linear form after which it may be investigated using the methods of the previous section.

For example, where $y = ax^2 + b$, y is a non-linear function of x, and it is not easy to tell how well data follows this relationship or to find the values of a

and b. However, after recasting this as $y = au + b$ where $u = x^2$, y is a linear function of u and has a straight line graph with slope a and y-intercept b.

Two further well known examples are the exponential and power law, which may be converted to linear form by the use of logarithms.

Thus the exponential:

$$y = a\exp(bx) \tag{0.4}$$

may be written as:

$$\log_\alpha y = \log_\alpha a + bx\log_\alpha e \tag{0.5}$$

When the base α is replaced by e or 10, this equation becomes:

$$\log_e y = \log_e a + bx \tag{0.6}$$

or

$$\log_{10} y = \log_{10} a + bx\log_{10} e$$

and $\log y$ is a linear function of x having a straight line graph with slope $b \log e$ and y-intercept $\log_{10}a$, as shown in Figure 0-2 below.

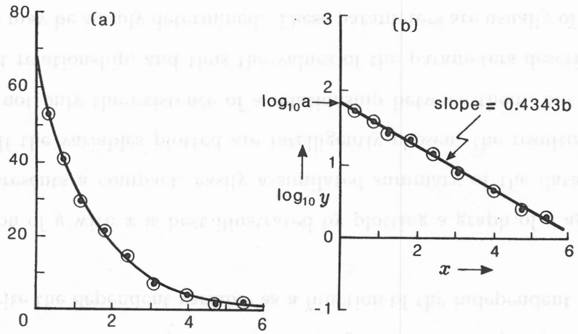


Figure 0-2

Similarly the power law:

$$y = ax^b \tag{0.7}$$

may be written as:

$$\log_{10} y = \log_{10} a + b\log_{10} x \tag{0.8}$$

and $\log_{10} y$ is a linear function of $\log_{10} x$ having a straight line graph with slope b and y-intercept $\log_{10} a$, as shown in Fig. 0-3 below.

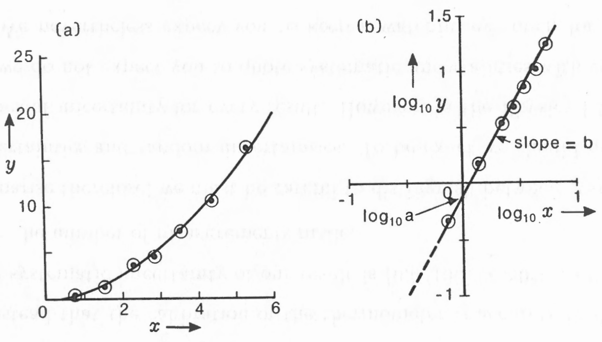


Fig. 0-3

The transformation to logarithms in Eq. (0.8) provides the most general method for dealing with the power law because it provides a method for determining the power b if this is not known. If b is known beforehand then straight lines could also be obtained by the alternative methods of plotting y against x^b or $\sqrt[b]{y}$ against x. These methods are used in the free-fall section of experiment 6.

2. Uncertainties

In carrying out an experiment we should always attempt to eliminate or minimise errors in our measurements. In addition, we should correct our data for any known errors that we have been unable to avoid but are nevertheless able to assess. Beyond that we will inevitably be aware that our results may contain unknown errors which we are unable to assess and therefore cannot correct for. We must therefore, estimate limits for these unknown errors, or, in other words, we must estimate an uncertainty for each result determined from our measurements. We need an estimate of uncertainty in order, for example, to compare our result meaningfully with results obtained by other experiments or with theoretical

predictions.

Results should therefore be expressed with an uncertainty, (e.g. Period of pendulum = 1.74 ± 0.03 s) so as to facilitate critical comparisons with other measurements or calculations. Different types of uncertainty (e.g. random; maximum; or systematic) can be defined, as discussed below and sometimes it may be appropriate to quote more than one kind (e.g. systematic as well as random) for a particular result.

2.1 Types of Uncertainty

To illustrate different types of uncertainty, consider an example. Suppose we make several measurements of a quantity x (e.g. measurements of the diameter of a cylinder, using a micrometer screw gauge; readings of the temperature of a solution, using a thermometer; or measurements of the time for ten oscillations of a simple pendulum, using a stopwatch). We notice that our individual readings of x vary randomly from measurement to measurement. This is reasonable because we know that our skill, our technique and our equipment all have their limitations. However, since the random errors are equally likely to be positive, and increase x, as to be negative, and decrease x, they should tend to cancel when a mean value is calculated from a large set of measurements of x. We can therefore reduce the overall random error by taking the mean value of many measurements of x. However, we can never be sure that this random error has been reduced to zero, therefore we must estimate a "random uncertainty" of the mean value. We do this as outlined in the next section, taking into account of the number of readings averaged and of the random variation from reading to reading.

The presence of random errors may thus be revealed by variations in the results obtained in successive measurements. What must we do, then, if we find no variations between the different readings of x? This could be caused by our technique or instruments not being precise enough to detect the random errors and variations (e.g. If we read the millimetre scale to the

nearest millimetre; or the thermometer to the nearest degree calibration; or the stopwatch only to the nearest second in the above examples). If this were the reason for no variation between readings of x then we should quote a "maximum uncertainty" for the "mean" value, which would correspond to one half of the division read (e.g. 0.5 mm; 0.5°C; and 0.5 s in the above examples).

We thus have either a random uncertainty or a maximum uncertainty to indicate the limits of unknown random errors in the mean value of a set of measurements x. In addition to these errors our measurements may contain other unknown errors which do not vary from measurement to measurement. Such errors are called systematic errors because they displace each of the measurements of x uniformly away from the true value. Sources of systematic error include, for instance, systematic faults in our instruments such as errors in their calibration or in their zero settings. Systematic errors, unlike random errors, can therefore not be reduced by averaging the readings obtained from a large number of measurements.

To illustrate by means of an example, if we use a thermometer, guaranteed by the manufacturer to be calibrated to an accuracy of 0.1°C, and determine a temperature to be 80.0°C, the systematic uncertainty of our measurements arising from the calibration is 0.1°C, whether our result is based on only one measurement or on many measurements. Likewise, if the manufacturer states instead that the calibration of the thermometer is accurate to 0.5% then the systematic uncertainty of our result is $(0.5/100) \times 80°\text{C} = 0.4°\text{C}$ whatever the number of measurements made.

To summarise therefore, we must be careful to distinguish between systematic uncertainties and random uncertainties. To be exact we should quote both types of uncertainty for every result. However, in the Physics I Laboratory we do not expect you to quote systematic uncertainties with every result. We nevertheless expect you to keep a watchful eye open for systematic errors, to correct these errors wherever possible and to note their presence, whenever appropriate. In dealing with random errors we must decide from inspection of our data whether we are able to estimate a random uncertainty; in other words, we must decide whether the data reveal variations from reading to reading which can be used to estimate the random uncertainty. If the answer to this question is negative then we must quote a maximum uncertainty. If it is positive we can estimate the random uncertainty as outlined in the next section.

2.2 Estimation of random uncertainties To estimate random uncertainties we turn to the laws of statistics which tell us (see e.g. Taylor: "An Introduction to Error Analysis") that if $\bar{x}$ is the mean value of n readings or estimates of x and if n is a large number, then these readings will form a "normal" or "Gaussian" distribution about x as shown in Fig. 0-4 below,

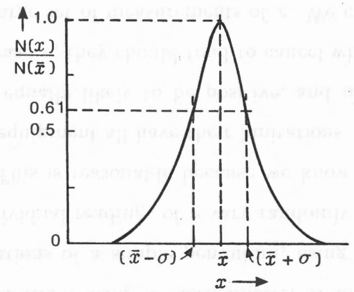


Fig. 0-4

and given by the equation:

$$N(x) = N(\bar{x}) \exp\left[-(x-\bar{x})^2/2\sigma^2\right] \qquad (0.9)$$ p29

where $N(x)$ is the number of readings per unit x in a small range of x centred on the value x, and the parameter σ^2 is called the variance of the distribution and is given by:

$$\sigma^2 = \frac{\Sigma(x-\bar{x})^2}{(n-1)} \qquad (0.10)$$

The square root of the variance is called the standard deviation of the distribution and is thus given by:

$$\sigma = \sqrt{\frac{\Sigma(x-\bar{x})^2}{(n-1)}} \tag{0.11}$$

Referring to Fig. 0-4 and applying Eq. 0.9 we see that $N(x)$ drops to the value 0.61 $N(\bar{x})$ at the x-values $(\bar{x}-\sigma)$ and $(\bar{x}-\sigma)$ on either side of the mean. By comparing the integral of the normal distribution from $(\bar{x}-\sigma)$ to $(\bar{x}+\sigma)$ with the integral from $-\infty$ to $+\infty$ we can show that 68%, or about 2/3, of the readings will fall in this interval.

Obviously the mean value $\bar{x}$ will be determined with better reproducibility than that of a single reading. A proper statistical treatment shows that if many sets of observations are done, and for each set n measurements are made and a mean value $\bar{x}$ calculated, these will themselves form a normal distribution with a standard deviation σ_m which is given by

$$\sigma_m = \sqrt{\frac{\Sigma(x-\bar{x})}{n(n-1)}} = \frac{\sigma_x}{\sqrt{n}} \tag{0.12}$$

The parameter σ_m is called the *standard deviation of the mean* and it is the preferred method for stating the estimated random uncertainty of the measured mean value $\bar{x}$. By using arguments similar to those used above for the standard deviation of an individual reading, we can show that there is a 68% probability that the "true" value of $\bar{x}$ (with no random errors) lies within the range $(\bar{x}-\sigma_m)$ to $(\bar{x}+\sigma_m)$.

An example illustrating the calculation of the mean, standard deviation, and standard deviation of the mean or random uncertainty is given below.

2.3 . Example of calculation of σ_m

The mean value $\bar{x}$ of the set of 12 measurements of x tabulated below is $\bar{x} = 43.59$. This mean value is temporarily rounded to 43.6 to simplify the arithmetic and the deviations δ shown in the second row of the table are calculated as above. The sum of the squares δ^2 listed in the third row of the table is 3.29.

if we only take one reading $\sigma = 0$, which is rubbish. There is always σ. So we use $n-1$, so σ is undefined for only one reading. If we take lots of readings as $N \gg 1$, $n-1 \xrightarrow[\text{to}]{\text{tends}} n$

as we take more and more readings, the standard deviation gets less and less. ∴ we use $\sqrt{n}$

$[\bar{x}-\sigma_m, \bar{x}+\sigma_m]$

$[\bar{x}-2\sigma_m, \bar{x}-2\sigma_m]$

x	=	43.3	44.6	44.1	43.0	43.4	43.7	43.2	42.7	43.4	44.3	43.8	43.6
δ	=	0.3	1.0	0.5	0.6	0.2	0.1	0.4	0.9	0.2	0.7	0.2	0.0
δ^2	=	0.09	1.0	0.25	0.36	0.04	0.01	0.16	0.81	0.04	0.49	0.04	0.00

Since $\Sigma\delta^2 = (x-\bar{x})^2$ we obtain from Eq. (11)

$$\sigma = \sqrt{\frac{\Sigma\delta^2}{(n-1)}} = \sqrt{\frac{3.29}{11}} = 0.547$$

Thus, from Eq. (12)

$$\sigma_m = \frac{\sigma}{\sqrt{n}} = \frac{0.547}{\sqrt{12}} = 0.158$$

Thus, our final result is

$$\bar{x} = 43.59 \pm 0.16$$

At this stage a few points should be made.

- σ defines the range within which roughly two thirds of the readings will fall. In our example above there were twelve readings and a value of 0.547 was obtained for σ. We would therefore expect to find (approximately) eight readings in the range 43.0 - 44.1 (i.e. $(\bar{x}-\sigma)$ to $(\bar{x}+\sigma)$). Indeed, this turns out to be the case.
- The standard deviation of the mean, σ_m, is also referred to as the *"uncertainty"* and represented by the symbol Δ (eg. in the above example the uncertainty in $\bar{x}$ is $\Delta x = 0.16$).
- The value obtained for σ_m is an estimate of the uncertainty in $\bar{x}$. It should therefore only be quoted to one or two significant figures. As a general rule, if our value is in the teens we may use two, while only one should be used if it is larger (eg. 0.16 could be left as is, while 0.73 should be rounded down to 0.7).
- It is actually the value of the uncertainty that determines the number of significant figures in the answer. Consider the case suggested above where we assumed that the uncertainty in our value of $\bar{x}$ was 0.7. If this were so this would imply that there is considerable uncertainty in

the value of the figure in the first decimal place of $\bar{x}$. It is therefore meaningless to quote any figure in the second decimal place and the answer should thus be recorded as $\bar{x} = 43.6 \pm 0.7$.

2.4 Uncertainties for slopes and intercepts for linear graphs

Since straight line graphs are particularly convenient and important in data analysis we need to know how to estimate uncertainties for the parameters, the slope and intercept, which we derive from these graphs. The preferred procedure for fitting a straight line to a set of data points, (x, y), is to apply the "method of least squares", which automatically provides "best" values, together with random uncertainties, for the slope and intercept.

2.5 The method of least squares

This method rests on the Principle of Least Squares which states that: "The most probably value of a quantity is obtained from a set of measurements by choosing the value which minimises the sum of the squares of the deviations of these measurements".

Thus, if a is the most probable value of the set of observations a_i and the deviation δ_i is defined by $\delta_i = a_i - a$ then the sum

$$s = \sum_{i=1}^{n} \delta_i^2 = \sum_{i=1}^{n} (a_i - a)^2$$

is a minimum where n is the no of measurements made.

This principle can be applied to fit a straight line $y = mx + c$ to a data set (x_i, y_i). The solutions for the unknowns m and c are

$$m = \frac{(n\ \Sigma xy - \Sigma x\ \Sigma y)}{D} \tag{0.13}$$

$$c = \frac{(\Sigma x^2\ \Sigma y - \Sigma xy\ \Sigma x)}{D} \tag{0.14}$$

$$\text{where } D = n\ \Sigma x^2 - (\Sigma x)^2 \tag{0.15}$$

and their variances are

$$\sigma_m^2 = \frac{\Sigma d^2}{D}\left(\frac{n}{n-2}\right) \tag{0.16}$$

$$\sigma_c^2 = \frac{\Sigma d^2\ \Sigma x^2}{nD}\left(\frac{n}{n-2}\right) \tag{0.17}$$

$$\text{where the deviation } d_i = y_i - (mx_i + c) \tag{0.18}$$

and the x and y and sums in Eqs. (0.13) to (0.18) are taken over $i = 1, n$

Thus to apply the least squares method one must first calculate Σx, Σy, Σx^2 and Σxy, from which m and c can be estimated from Eqs. (0. 13) and (0.14) using Eq. (0.15). The variances σ_m^2 and σ_c^2 can then be found from Eqs. (0.16) and (0. 17) using Eq. (0.18).

A computer is best used to do the calculation. The microcomputers in the Physics I laboratory have been programmed to do a least squares fit. Use these whenever you need to find a slope and its uncertainty.

2.6 Fractional and percentage uncertainty

The normal method for stating uncertainties is to express them in absolute form, as in the example shown above. Here the value 0.16 is a statement of the estimated absolute random uncertainty. It may also be convenient on occasion to express the uncertainty Δx as a fraction, or as a percentage, of the measured quantity x. Thus we may sometimes refer to the fractional uncertainty given by $\Delta x/x$ or to the percentage uncertainty given by $100 \times (\Delta x/x)\%$. For example the fractional uncertainty of the mean x is $0.16/43.59 = 3.7 \times 10^{-3}$ and the percentage uncertainty is $100 \times 3.7 \times 10^{-3} = 0.37\%$.

2.7 Propagation of uncertainties

When we derive a quantity y from a set of measurements of m other quantities, x_1, x_2, $x_3 \ldots x_m$ we need to know how to estimate the uncertainty of y from our estimates of the uncertainties of the m measured quantities. The general formulae for dealing with this problem involve the use of partial differentials which you will probably not be familiar with yet, even if you are taking Mathematics I. (Maths I students will deal with partial differentiation later in the year.) We therefore leave you only with the caution that

the uncertainty of y is not in general simply the sum of the uncertainties of $x_1, x_2, \ldots x_m$.

Where the analysis of your experimental data requires you to deal with problems of this sort we will provide you with the formulae which should be used to estimate the uncertainty of the derived quantity y in each case. A short summary of the formulae required for some commonly occurring functions is presented below.

Type of equation from which result R is to be calculated	Formula for calculating the uncertainty R
$R = A \pm B$	$\Delta R = \sqrt{\Delta A^2 + \Delta B^2}$
$R = A \times B$ and $R = A/B$	$\Delta R/R = \sqrt{(\Delta A/A)^2 + (\Delta B/B)^2}$
$R = A^x$	$\Delta R/R = x\Delta A/A$
$R = A^x B^y$	$\Delta R/R = \sqrt{(x\ \Delta A/A)^2 + (y\ \Delta B/B)^2}$

* Note if $R = a\ A \pm bB$, where a and b are constants, then the uncertainty in R is given by $\Delta R = \sqrt{(a\Delta A)^2 + (b\Delta B)^2}$.

Constant multipliers do not alter the other three equations.

$$\text{e.g.} \quad \text{if } R = aA^x \text{ then } \frac{\Delta R}{R} = x\frac{\Delta A}{A}$$

Experiment 1

Hooke's Law

References:

Giancoli (3rd Ed) 11-1, 3

Haliday, Resnick & Walker (4th Ed) 7-4

1.1 Aim

The aim of this experiment is to verify Hooke's law for a spiral spring and then to determine the force constant of the spring.

1.2 Introduction

Hooke's law states that the force, F, required to stretch a spiral spring is (directly) proportional to the extension, x, of the spring. Mathematically Hooke's law is written

$$F = kx, \tag{1.1}$$

where k is the constant of proportionality and is known as the *force constant* of the spring. (The force constant is a measure of the *stiffness* of the spring – the stiffer the spring the larger the force constant.) In this experiment you will verify Hooke's law by plotting a graph and then use the graph to determine the force constant of the spring.

1.3 Apparatus

You are supplied with a spring suspended from a retort stand, a small bucket, a number of ball bearings of known mass, and a metre stick.

1.4 Measurement of force and extension

In this experiment a force is applied to the spiral spring by hanging a weight of known mass to the end of the spring. If the weight has a mass m the force exerted on the spring is just mg, and is therefore easily established. The extension produced by the applied force can also easily be measured with the aid of the metre stick.

Begin by attaching the bucket to the end of the spring and measuring the position of the pointer fixed to the end of the spring. Now add the ball bearings one at a time, measuring the new position of the pointer. Hence determine the extension produced by the force of the "weight" on the spring. Use the fact that the ball bearings each have a mass of 16.4 grams to determine the weight of the balls in the bucket. (You can assume $g = 9.80$ m s^{-2}.) If you have time, use one of the triple beam balances to confirm the mass of the ball bearings. Tabulate your results as shown below, recording the appropriate number of *significant figures*.

TABLE 1.1: Force vs Spring Extension

Mass g	Force N	Pointer pos^n cm	Extension cm
0.0	0.0	0.0	

Plot a graph of force versus extension. If you obtain a straight-line graph passing through the origin the extension is directly proportional to the force exerted on the spring, and you will thus have verified Hooke's law. The force constant of the spring

is given by the slope of the straight-line graph. Measure the slope of your graph by choosing two convenient points on the line. Remember to choose points sufficiently far apart and *not to use any of the the plotted points* when calculating the slope.

Experiment 2

Random Fluctuations and the Normal Distribution

Reference:

Physics 1 Laboratory Manual: Data Analysis

2.1 Aim

To investigate random fluctuations in observations of the decay rate of a radioactive source, to determine the frequency distribution of these fluctuations and to estimate the standard deviations of this distribution and of the observed average decay rate.

2.2 Introduction

Radioactive decay is a process in which an unstable atomic nucleus changes to a more stable form. The decay is usually accompanied by the emission of radiation (e.g. α, β or γ) which can be observed by means of a Geiger counter. Each unstable nucleus has a definite probability for decaying in any one-second interval. If we knew both this probability (for the particular unstable nuclear species) and the number of unstable nuclei in our radioactive source then we could calculate the expected average number of decays in that source in one second. However, each nucleus decays at a random time so that the number of decays per second we can expect to obtain gives results which spread over a range of values extending above and below the average value. A plot of

these values in the form of a histogram will indicate the frequency distribution of the observed decay rate.

The form of this distribution can be predicated from theoretical considerations. Since radioactive decay is a random process, it can be shown that a histogram consistent with the 'normal' or 'Gaussian' distribution should be observed, provided the number of decays which are registered in each measurement is sufficiently large (> 40).

The first objective of this experiment is to check whether the frequency distribution of a set of count rate measurements obtained under identical conditions is consistent with the predicted Gaussian form. Random variations or errors of one kind or another are encountered in virtually every experimental measurement. Therefore the distribution which you observe in this experiment with the radioactive source is typical of what you must expect in all other experiments. To express the estimated extent of random errors or uncertainties we use standard deviations as defined in section 2.2 of your introductory notes on data analysis. The second objective of this experiment is to compare the standard deviation of your result obtained graphically with that obtained by detailed calculation.

It is also possible to estimate the standard deviation of a random process such as radioactivity from a single reading as discussed in 2.4. The third objective is therefore to compare the standard deviation obtained in this manner with those obtained by the other methods.

2.3 Apparatus

A radioactive source (^{60}Co) is provided together with a Geiger counter and a scalar unit including a built-in electronic timer. The Geiger counter will be set up and checked for you in advance, so do not adjust the operating conditions.

2.4 Measurements and analysis

The count rate recorded by the Geiger may be adjusted by varying the distance between it and the ^{60}Co source. Adjust this distance until the counts recorded in a timing interval of 10 s number between 400 and 500, then ensure that the source is not moved during the remainder of the experiment. (If available, use a piece of masking tape to secure the source mounting stand to the measuring bench.)

Using a timing interval of 10 s, take 100 or more independent readings of the count recorded by the Geiger. These readings must be neatly recorded, e.g. in a table of 5 columns with each column containing 20 numbers. To speed up the recording of this experiment it is suggested that both members of the pair *individually* record the data into their books as the measurements are taken. Plot the readings in a histogram using an interval of 10 counts, as shown in Fig 2.1. Draw a 'best-fit' smooth Gaussian-like curve over your histogram.

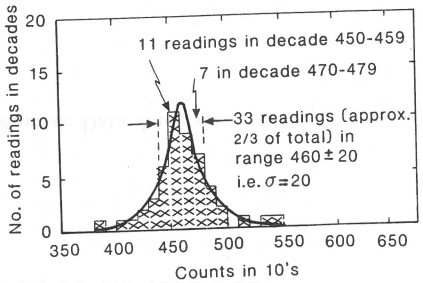


Figure 2-1

A working criterion for obtaining a 'best-fit' is that vacant area (unfilled histogram squares) below the curve should be approximately equal to the filled area extending above the curve. Students often find drawing the curve a difficult task. It is slightly easier if one knows the point about which the symmetrical bell-shaped curve is to be

drawn. Therefore begin by calculating the average count rate per 10 s all of the count readings. Now draw the 'best-fit' curve using the criteria discussed above. *Please note that the maximum of the curve does not have to be the same as the maximum value of the histogram.*

Next determine the standard deviation for a single count reading, σ, by three different methods.

First, determine the standard deviation, σ, graphically. Do this by determining the half-width of the 'best-fit' curve at 0.61 of its maximum value. (See section 2.2 of the Introduction.)

Next determine σ by calculation. If your calculator has a statistical package which allows you to determine the standard deviation use that. If not, take 10 readings at random from your results and carry out the calculation of σ as discussed in section 2.2.3. You should also check to see whether 2/3 of your measured values fall between (mean $-\sigma$) and (mean $+\sigma$). The standard deviation of the average (or mean), σ_m, of the observed counts (per 10 s) should also be determined.

Finally, it can be shown that for the radioactive decay process the standard deviation σ of a single observation can be estimated from the simple equation

$$\sigma = \sqrt{N}$$

where N is the number of decays recorded in a typical 10 s reading. Use this method to obtain an estimate for σ and compare it with the values you obtained by the other methods. Does it give a reasonable value for σ?

NOTE:

Strictly speaking the distribution one measures for the radioactive decay rate is a Poisson distribution. However, it can be shown that as the average number N becomes large (i.e. greater than about 40) it approaches a Gaussian distribution. It is therefore expected that with N somewhere between 400 and 500 the distribution you will obtain will be indistinguishable from a Gaussian distribution, provided you take a sufficient number of readings.

Experiment 3

The Simple Pendulum

References:
Giancoli (3rd Ed) 11-4
Halliday, Resnick & Walker (4th Ed) 14-6

3.1 Aim

To verify the form of the relationship between the period and length of a simple pendulum and having done so to measure "g" and determine the error associated with this measurement

3.2 Introduction

A pendulum consists of a bob (a mass) attached to a string that is fastened so that the pendulum can swing or oscillate in a plane (see Fig. 3-1). For a simple pendulum all the mass is considered to be concentrated at the centre of the bob.

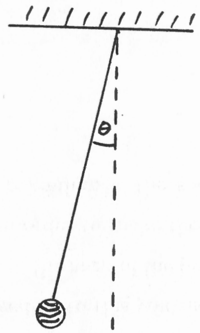


Figure 3-1

Providing the oscillations are small the motion of the pendulum approximates to simple harmonic motion and the relationship between the period T and the length L of a simple pendulum is given by

$$T = 2\pi\sqrt{L/g} \tag{3.1}$$

where g is the acceleration due to gravity.

3.3 Confirmation of form of relationship

Your first task is to verify the form of this relationship. Set up a pendulum using the metal bob and string. Set it swinging in small oscillations. (A pendulum's oscillations are described as "small" if the angle between the equilibrium position of the pendulum and the position of maximum displacement is small - less than ten degrees. If you swing your pendulum as high as it will go, the above relation will not be valid).

Because most of the error in timing is introduced during starting and stopping the stopwatch it is more accurate to time several successive oscillations together and then to divide by their number to obtain the time taken for a single oscillation. In deciding how many oscillations to measure you should consider how much error you are likely to introduce in starting and stopping the stopwatch and also how much error you are willing to tolerate in making the measurement. Generally it is not unreasonable to expect to take 20 to 30 s to make such a measurement and you should therefore establish how many oscillations this would correspond to - say to the nearest 5 or 10 oscillations. (Note - if the period of the oscillations varies during a set of measurements there is nothing stopping you varying the number of oscillations provided that you note this in your table of results.) Next decide at which point in the oscillation you should start (and stop) the stopwatch.

Once the preliminary investigation has been completed you can start to vary L, the string length. (Note that L is measured from the point of support to the centre of the bob.) Measure the period for 5 or 6 different values of L, taking at least 3 readings

for each. Cover a range from about 0.5 m to about 1.5 m. Draw up a table displaying your measured periods and corresponding string lengths and plot a suitable graph to verify the T vs L relationship given in Eq. 3.1.

Having verified the relationship between T and L your next task is to measure g, the acceleration due to gravity. However before proceeding to this you should quickly convince yourself that the period really is independent of the mass of the pendulum bob by replacing the bob with one of a different mass. In order to make the comparison easier it is useful to ensure that the length of the pendulum is the same for both measurements.

3.4 Measurement of "g"

Choose a fairly long string-length and measure the length 3 or 4 times. Next obtain 10 readings of 50 oscillations. The most obvious method of obtaining these would be to take 10 successive readings of 50 oscillations. This method may be a little time consuming. An alternative method which will save you time is the "method of halves". For this one sets the pendulum swinging and then times groups of 5 oscillations. Do not stop between readings, but note the time for 0,5,10, ... and 100 oscillations. (You will find it easier if one person calls out the times to the other who records them. Alternatively if your stopwatch has a lap timer it is easier for one to count the oscillations and stop the watch using the lap timer every five oscillations while the partner records the times.) Now subtract the time for 0 oscillations from that for 50, 5 from that for 55, 10 from 60, etc. and you will end up with 10 readings for 50 oscillations having only measured over 100 oscillations. Neat - isn't it? Use either of the above methods. Find the average values of T and L and use them to determine your value of g.

Now use the method described in the earlier lecture to determine the uncertainty in your values of T and L. (In the case of L if, because of the crudeness of your measuring instrument, there is no variation in your readings, use the least count of the instrument as an estimate of the uncertainty.) Now, with the aid of the table on page xxV of the

Introduction to this manual, determine the uncertainty associated with your value of g. Compare your value of g (and its uncertainty) with the accepted value of 9.80 m s^{-2}, and thus decide whether your measurement errors are likely to be systematic or random. Use this to suggest possible sources of error.

Experiment 4

Lenses and their focal lengths

References:

Giancoli (3rd Ed) 23-7

Halliday, Resnick & Walker (4th Ed) 39-9

4.1 Aim

To determine the focal length of thin converging and diverging lenses.

4.2 Introduction

Thin lenses and mirrors are used extensively in scientific and other equipment (e.g. in telescopes, microscopes and cameras). Basic to their operation is the theory of geometrical optics, which deals primarily with mirrors and thin lenses and which you will have covered in your lecture course.

In the first part of this experiment you will use the method of parallax described in Appendix A, to which you should refer before reading any further.

4.3 Focal Length of a Thin Converging Lens

Each student should take one reading by each of the following methods.

4.3.1 Distant object method

Arrange the optical bench so that light from an illuminated object at least 10 m away (e.g. windows at the FAR side of the laboratory) falls on the lens. Set up the white screen on the opposite side of the lens, adjusting its position until the image of the window is sharply focused on the screen. The distance between the lens and the screen is then the focal length of the lens.

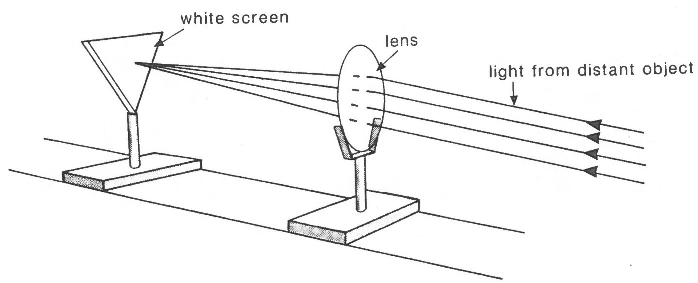


Figure 4-1

4.3.2 Parallax Method

Remove the screen and replace it with a pin. Looking through the lens, adjust the position of the pin so that there is no parallax between the pin and the image of the window. The pin now marks the position of the image. The distance from the lens to the pin is the focal length of the lens.

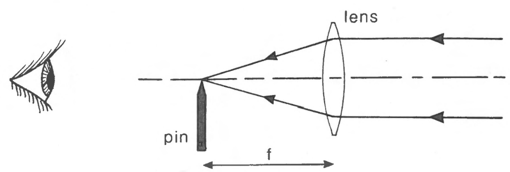


Figure 4-2

4.3.3 Returned-Image Method

Place a plane mirror a few centimetres behind the lens and parallel to it. Place a pin in front of the lens, approximately at the focal point. Adjust the angle of the plane mirror, and the height of the pin, until you locate the inverted image of the pin. Arrange it so that the object and image just meet, point to point.

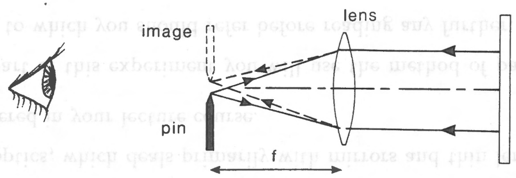


Figure 4-3

Now adjust the position of the object pin until there is no parallax between it and its image. The distance between the pin and the lens is then the focal length of the lens.

4.3.4 Method of Conjugate Foci

The members of a pair should take turns to set up the pins and read off their positions. This method makes use of the thin lens formula

$$\frac{1}{v} + \frac{1}{u} = \frac{1}{f}$$

where f = focal length of lens
u = object-to-lens distance
v = image-to-lens distance

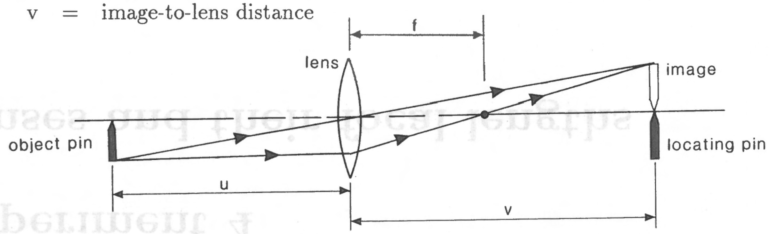


Figure 4-4

Place the lens at the centre mark of the optical bench and the object pin about 50 cm from the lens. Looking from the opposite side of the lens, locate the inverted image

of the object pin. Now use the locating pin to mark the position of the image, by the method of no parallax. Record the positions of the object pin, lens and locating pin.

Move the object pin a few centimetres closer to the lens. Locate the image as before, recording your new set of readings.

Repeat until you have four or five sets of readings. Then calculate u, v, 1/u, 1/v and finally 1/f and hence f, tabulating readings and calculations. Finally find the mean value of f.

4.4 Focal Length of a Diverging Lens

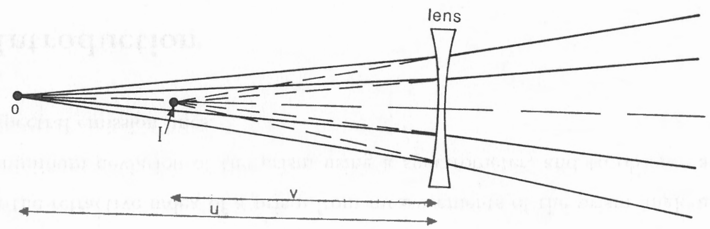


Figure 4-5

If an object O is placed in front of a diverting lens, then a virtual image I is formed in front of the lens (see Fig. 4-5). This image is said to be virtual because rays do not actually pass through this point but on emerging from the lens appear to have emanated from it. In order to calculate f, we need to know u and v, but we can't measure v by any method described previously in section 4.3. (Why not?) However if we were to place a converging mirror behind the lens and position it such that the rays emerging from the lens strike it perpendicularly, then the rays would all be reflected back along the path they came and an image would be formed back at the original object (see Fig. 4-6).

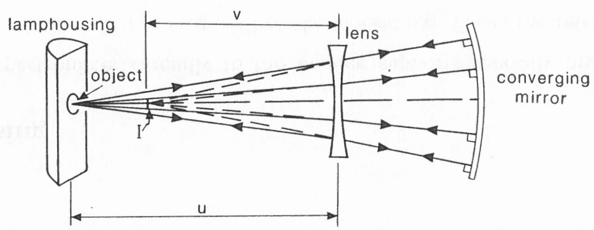


Figure 4-6

Now if the rays strike the mirror perpendicularly, then they must appear to emanate from the centre of curvature of the mirror and thus the position of the virtual image formed by the lens is at the centre of curvature of the mirror. Therefore, the way to proceed is to fix the mirror in a certain position and first obtain the position of the centre of curvature by positioning the lamphousing such that the image is formed back at the lamphousing. Repeat the measurement three or four times.

Now place the lens *between the position of the centre of curvature of the mirror* and move the lamphousing back until you find a position where a sharp image is thrown back onto the face of the lamphousing. Care should be taken to ensure that your image is not formed from a reflection off the front face of the lens. This can be easily checked by placing your hand between the lens and the mirror - if the image does not disappear it has been formed from a reflection from the lens.

Measure the object and image distances. (Remember that the image distance is now the distance from the position of the centre of curvature to the lens.) Now move the position of the lens by a couple of cm. (DO NOT MOVE THE POSITION OF THE MIRROR) and repeat the measurement. Having obtained five such measurements, use the formula $1/v + 1/u = 1/f$ to determine the focal length of the diverging lens.

Experiment 5

Refractive index of a prism

References:

Giancoli (3rd Ed) 23 Problem 68, 24-4, 23-5

Halliday, Resnick & Walker (4th Ed) Ch 39 Problem 14

5.1 Aim

To obtain the refractive index of a prism from measurements of the prism angle and angle of minimum deviation of the prism using a spectrometer, and to observe and examine spectral emission lines.

5.2 Introduction

In this experiment you will use a spectrometer to measure the angle of a glass prism, and the angle of minimum deviation of a beam refracted through the prism. From these two measurements the refractive index of the glass is calculated.

5.3 Apparatus: The Spectrometer

5.3.1 Description

The spectrometer is an instrument for the measurement of angles of deviation of light rays resulting from reflection, refraction or diffraction. Its essential features are shown in Fig. 5-1 below:

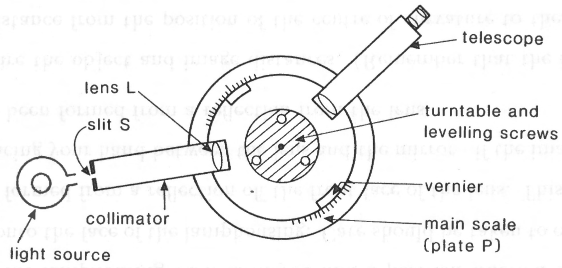


Figure 5-1

A circular horizontal plate P which carries the main scale graduated in degrees is mounted on a vertical column that also carries the telescope.

The collimator consists of a tube carrying a slit S of adjustable width and so mounted that it can be placed in the principal focus of the lens L. This arrangement makes it possible to regard slit S as an infinitely distant line- source of light, for waves (light rays) that originate at S become plane waves (parallel rays) after passing through L.

If you examine the spectrometer you will see several screws and clamps that are used in adjusting the instrument. The spectrometers have already had their turntables levelled, so do not touch the three turntable levelling screws. Examine the various clamps to acquaint yourself with their features and consult a demonstrator if you are unsure of how they are used.

5.3.2 Focussing

Carry the whole spectrometer carefully to the wooden supports specially provided next to the louvre windows in the East wall of the laboratory. Focus the telescope,

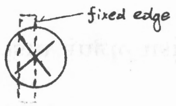
following the instructions given in the appendix 'Focussing microscopes and telescopes' in this manual. Carry the spectrometer carefully back to its place in the darkroom, without disturbing the telescope. Rotate the telescope until it is directly opposite and in alignment with the collimator. Open the slit of the collimator to a width of about 0.5 mm, and check that it is vertical. Illuminate the slit using the sodium lamp provided, then look through the telescope for the image of the collimator slit. You should see a blurred bright line instead of a clear image of the slit. Do not refocus the telescope, but adjust the draw tube of the collimator until the image of the slit can be seen distinctly and without parallax with respect to the crosswires of the telescope. The collimator now produces a beam of parallel light rays.

5.3.3 Using the spectrometer

The spectrometer is now adjusted for use in this experiment. Do not change the settings of the eyepiece, telescope and collimator during the course of the experiment. In order to swivel the telescope, handle only the arm to which it is attached, and not the telescope itself. All readings should be taken by aligning the crosswires with the fixed side of the slit. For ease of taking readings, the crosswires should be arranged at about 45^0 with respect to the slit, rather than parallel and perpendicular to it. To achieve greater accuracy, make the collimator slit as narrow as possible while still remaining clearly visible. To take readings accurately, set the crosswires on the fixed side of the image of the slit, clamp the telescope and use the fine adjustment provided by the tangent screw to obtain an exact setting.

The spectrometer has two vernier scales for accurate measurements of angles. Examine the verniers carefully to be sure you know how to read them. Readings should be taken to the nearest minute of arc. When the telescope is shifted from one position to another, one of the verniers may move past the 360^0 mark of the circular scale. This must be taken into account when calculating the differences between the two positions.

Thus



is better than

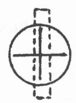


Figure 5-2

To read the verniers one must first establish the *least count*

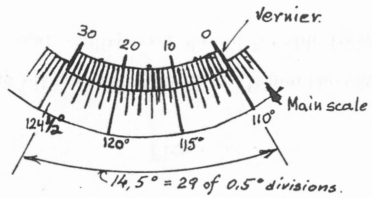


Figure 5-3

Observe the size of the smallest divisions of the main scale and the number of divisions on the vernier. If the smallest division on the main scale is 0.5 and 30 vernier divisions are equal to 29 main scale divisions the least count is: $1/2 \times 1/30 = 1/60 = 1$ minute of arc of ($1'$).

As an exercise check the reading in the sketch.

The reading as shown in sketch is thus:

$114°30' +$ vernier reading coinciding with a mark on the main scale
$= 114°30' + 14' = 114°44' \pm 1'$

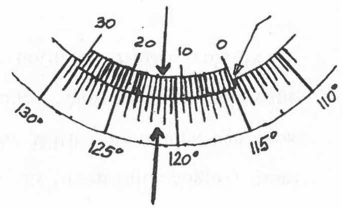


Figure 5-4

5.4 Method

5.4.1 Prism angle using reflection

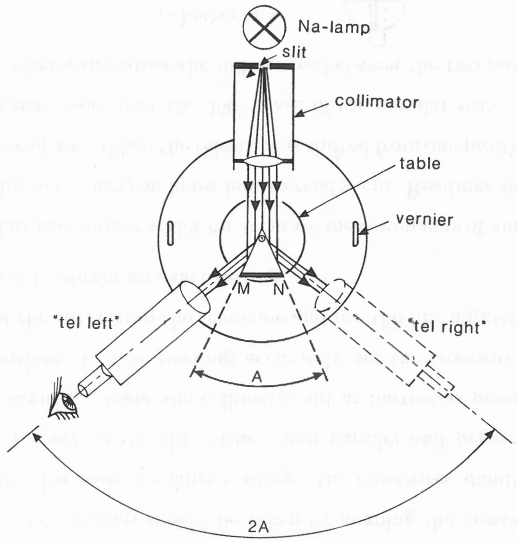


Figure 5-5

To measure the angle of the prism, the reflected image of the slit from each of the two prism faces forming the prism angle is observed, as shown in the figure above. The difference of these readings gives $2 \times A$. Place the prism on the spectrometer table with the ground (matt) face MN approximately perpendicular to the axis of the collimator. The refracting edge should be over the centre of the table. In this position the prism splits the parallel beam of light from the collimator and reflects a portion of it from each of the polished faces. Using the sodium lamp, try to locate the reflected images of the slit with the unaided eye first. Then adjust the slit width to give a narrow slit, and take several readings of the telescope in each position. Tabulate the readings, and calculate the angle of the prism, giving the mean value, and the uncertainty.

5.4.2 Angle of minimum deviation and spectral lines using refraction

Much physical and chemical information can be deduced from the examination of substance's spectral lines. The spectrum can be observed in absorption or emission, and the wavelengths of the lines are characteristic of a particular substance. In this section the emission spectra of sodium are examined.

To observe the spectrum of a substance with a prism, the incident beam must be refracted by the prism. The refracted beam is observed with the telescope, and is seen to be deviated through an angle D, called the *angle of deviation.* D is the angle between an undeviated beam and the refracted beam (see Fig. 5-6). The refractive index of the prism depends on the wavelengths of the incident beam, thus each characteristic wavelength constituting the emission spectrum of the light source is deviated a different amount, resulting in resolution of the spectrum (i.e. a spatial separation of the characteristic wavelengths).

Leaving the prism set up as in experiment 5.4.1, rotate the prism table slightly more than 90^0 so that it is in the position shown in Fig. 5-6. With the unaided eye, look along the direction TB until you see the spectrum (colours). Now move the telescope into position and examine the spectrum more carefully, noting how many colours are seen.

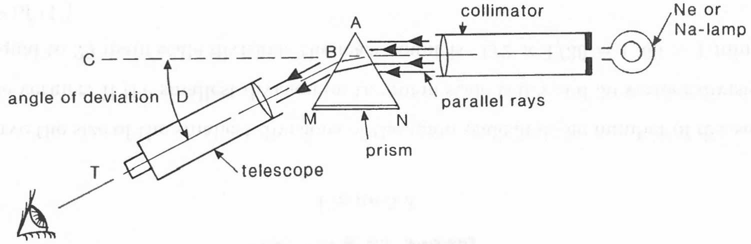


Figure 5-6

Change the width of the slit and note the effect. When the slit is made very narrow and the spectrometer is of good quality, you should be able to see the "sodium doublet",

i.e. two bright yellow lines of the sodium spectrum. If the quality of the instrument is poorer or the slit too wide, the doublet merges into one broad yellow line.

While observing the sodium yellow line, rotate the prism table slightly. The spectrum will move, i.e. the angle of deviation, D, is altered. Slowly rotate the prism table in the direction which causes the spectrum to move towards C (axis of the collimator). Follow the motion of the yellow line with the telescope until the line has moved towards C as far as possible, i.e. the angle of deviation, D, is at its minimum.
The position where the angle D is the smallest is called the *position of minimum deviation* and the corresponding value of D is called the *angle of minimum deviation*, D_{min}. This angle is unique for a particular prism and spectral line. Note that once the prism has been set in the position of minimum deviation, rotation of the prism table in either direction increases angle D, i.e. moves the line away from the central position C.

For the angle of minimum deviation, readings with the telescope left and right are taken, as in section 5.4.1. In addition to rotating the telescope, the prism has to be in the minimum deviation position for each telescope position. To achieve this, the table carrying the prism is rotated from position 1 for telescope left to position 2 for telescope right (see Fig. 5-7), i.e. the table *and* the telescope must be rotated for each reading, and the table has to be set to give the minimum angle of deviation for each reading.

NOTE: DO NOT MOVE THE POSITION OF THE PRISM ON THE TABLE.

Position 1 : Tel. left

Position 2 : Tel. right

Figure 5-7

Repeat both positions a number of times, alternately. Tabulate all the readings and obtain a value for $2D_{min}$, find the mean of these, and hence find D_{min} and its uncertainty. Finally calculate the refractive index μ from the formula

$$\mu = \frac{\sin \frac{1}{2}(A + D_{min})}{\sin \frac{1}{2}A}.$$

Addendum

You have determined values for the uncertainties of A and D_{min}. An uncertainty for the refractive index could be calculated from these. Can you suggest how this would be done?

Experiment 6

Free-Fall

References:

Giancoli (3rd Ed.) 2-10

Halliday, Resnick & Walker (4th Ed.) 2-8

6.1 Aim

To measure g, the acceleration due to gravity, using a free- fall apparatus to time the fall of a ball-bearing over a known distance.

6.2 Method

The layout of the apparatus for this experiment is illustrated schematically below. It is not necessary to set it up; this has already been done. The start/stop switch of the Universal Counter starts the timer and at the same time releases the ball. The "stop" switch is a piezoelectric switch which has been moulded into the platform at the bottom of your retort stand. The piezoelectric switch is activated by the impact of the falling ball.

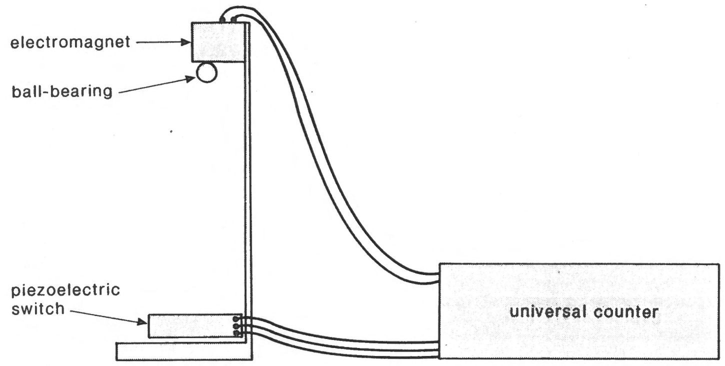


Figure 6-1

Set the start/stop switch on the Universal Counter to the stop position. "Reset" the counter and attach the ball to the electromagnet at the top of the stand. "Start" the counter. This switches off the electromagnet releasing the ball. When the ball strikes the platform at the base the counter should stop timing. Check that your apparatus is working correctly.

Measure the time, t, taken for the ball to fall a distance x, over a range of at least six different x-values between 0.2 m and 0.7 m (approximately). Take several readings at each height and determine the mean of these. You should then have 6 values of x and the corresponding (mean) t.

Note that x is the distance the ball falls. Since the timer will be stopped by the **BOTTOM** of the ball, from where should x be measured?

6.3 Analysis

For an object falling freely (ignoring air resistance) we know

$$x = ut + \frac{1}{2}at^2$$

In this experiment, $u = 0$ and $a = g$. Thus the above equation reduces to

$$x = \frac{1}{2}gt^2$$

so that a graph of t^2 plotted against x should have slope $2/g$, (distance x being the independent variable). Alternatively a graph of t against $\sqrt{x}$ should have a slope of $\sqrt{2/g}$.

Both of these methods are valid, but it is suggested that you use the latter. The reason for this is that any systematic timing error can be clearly identified.

Tabulate your results and plot a graph from which a value of g can be determined. Use the microcomputer to obtain a least squares fit of your data (see Section II.2.6) and the actual error associated with your slope.

Is your value for g a reasonable one? (cf. 9.80 m s^{-2}). What do you think are the main sources of error in this experiment?

Experiment 7

Newton's Second Law

References:

Giancoli (3rd Ed) Ch. 4

Halliday, Resnick & Walker (4th Ed) 5-5

7.1 Aim

To verify Newton's Second Law, $f = ma$, by applying different forces to a mass on a frictionless air-track.

7.2 Theory

A falling mass, m, applies a force to a glider of mass M by means of a tape joining the two bodies. The glider moves on a nearly frictionless surface, and the friction of the air- pulley can also be regarded as negligible.

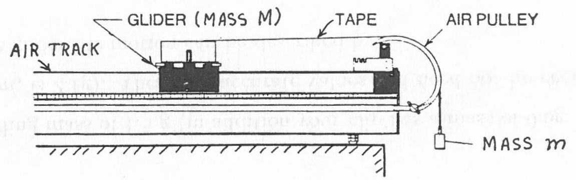


Figure 7-1

Assuming Newton's Second Law to be valid, the equations of motion for the two bodies can be written

$$\begin{aligned} mg - T &= ma \\ T &= Ma \end{aligned}$$

where T is the tension in the tape, and the two bodies have the same magnitude of acceleration, a, though of course they accelerate in different directions.

Eliminating T, we have

$$mg = (M+m)a$$

or

$$a = \frac{g}{(M+m)} \cdot m \qquad (7.1)$$

Thus we see that if $(M+m)$, the total mass undergoing acceleration, is kept constant the acceleration of the glider is directly proportional to the mass m. In this experiment we keep the 'total mass' constant by placing all those weights which are not being used to provide the 'accelerating' force on the glider pin and merely transfer them to the end of the tape as required. M is therefore the total mass of the glider PLUS that of the weights mounted on top of it.

7.3 Method

The air-track provides an air cushion on which a glider can move with negligible friction. (Note: Air-tracks and gliders are expensive and carefully aligned pieces of equipment - do not bump, bend, drop (!) or dirty them, or slide the gliders when the air-track is switched off.) The photocell and timing system allows time intervals to be measured very accurately, using light-sensitive detectors.

Your demonstrator will show you how to operate the air-track and timing system, and will indicate a suitable range of distance measurements to make in order to determine 'a'.

First use a pulling mass of 1.5 g (in addition your clip has a mass of 0.6g, so the total pulling mass, m, is 2.1g). These are accurate values and need not be checked. When you release the glider, its motion can be described by

$$x = ut + \frac{1}{2}at^2$$

Note that this formula is valid ONLY if acceleration, a, is constant. Dividing through by t, we have

$$\frac{x}{t} = u + \frac{1}{2}at$$

Thus a graph of x/t against t should be a straight line of slope $\frac{1}{2}a$. Take at least 6 readings of x and t over a wide range of x, and plot these in your book. Is the acceleration of the glider constant? What is its value?

Now repeat the experiment, using 3.0g, 4.5g and 6.0g as pulling masses (plus the clip mass). For each of these, take at least 6 readings and plot your results on the SAME graph as before. (To save time you may plot two graphs and your partner the other two.)

You should thus determine 4 values of 'a' corresponding to 4 values of m.

Now draw another graph, plotting a against m. If this proves to be a straight line, you have verified Newton's Second Law (since it was the basis of the derivation of Eq.7.1)

Experiment 8

Rotational Dynamics

References:

Giancoli (3rd Ed) 8-3,4,5,6

Halliday, Resnick & Walker (4th Ed) 11-6,7,8,10

There are two parts to this experiment and they may be done in any order. In Experiment 8.1 we examine the situation where rotational motion occurs separately from translational motion, while in Experiment 8.2 we examine the situation where they occur simultaneously. The approach that we shall adopt in treating both sections is the principle of Conservation of Energy. It is assumed that you are familiar with this principle and with the equations of translational and rotational motion.

8.1 The Flywheel

8.1.1 Aim

To measure the moment of inertia of a flywheel and then to determine how the initial potential energy in the system is converted into other forms of energy.

8.1.2 Theory

Suppose the mass of the suspended weight is m and the radius of the flywheel axle is r. When the mass is released at point A it falls through a distance s causing the flywheel

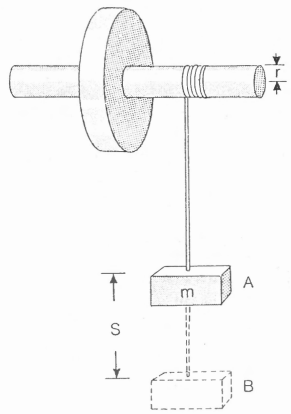


Fig. 8-1

to rotate n times. In falling the mass loses potential energy mgs. At the same time it acquires translational kinetic energy $\frac{1}{2}mv^2$ while the flywheel which has begun to rotate has acquired rotational kinetic energy $\frac{1}{2}I\omega^2$. (Here v is the velocity of the mass m and ω is the angular velocity of the flywheel when the mass has reached point B). In addition work has been done against the retarding frictional torque τ. (Rotational work done against τ is $\tau\theta$ which equals $2\pi n\tau$.

By the principle of Conservation of Energy we have:

decrease in PE = increase in KE(trans) + increase in KE(rot) + work done against friction

$$mgs = \tfrac{1}{2}mv^2 + \tfrac{1}{2}I\omega^2 + 2\pi n\tau \tag{8.1}$$

In order to determine I we therefore first need to determine the magnitude of the retarding torque τ. This is done as follows.

Suppose the mass is released at B. The torque which had originally caused the rotational acceleration now no longer exists. However the frictional torque still does, and under the action of this retarding torque the flywheel will slow down eventually coming to

rest. Suppose that after the release of m at point B the flywheel makes a further N revolutions before coming to rest. The work done against friction during these n revolutions is just equal to the change in the rotational kinetic energy. i.e. Work done against torque = decrease in KE(rot).

i.e. $\tau 2\pi N = \frac{1}{2} I\omega^2$

therefore

$$\tau = \frac{I\omega^2}{4\pi N}$$

and on substitution in Eq. 8.1 we get

$$\begin{aligned} mgs &= \tfrac{1}{2}mv^2 + \tfrac{1}{2}I\omega^2 + \tfrac{1}{2}I\omega^2\frac{n}{N} \\ \text{or } mgs &= \tfrac{1}{2}mv^2 + \tfrac{1}{2}I\omega^2\left(\frac{N+n}{N}\right) \end{aligned} \tag{8.2}$$

The average velocity of mass m is $\bar{v} = s/t$ and since the mass starts from rest the final velocity $V = 2\bar{v} = 2s/t$, where t is the time taken to fall through a distance s. In addition since

$$\omega = \frac{V}{r}$$

the final angular velocity is given by $\omega = 2s/rt$. Thus Eq. 8.2 becomes

$$mgs = \frac{2ms^2}{t^2} + \frac{2Is^2}{r^2t^2}\frac{(N+n)}{N}$$

and on multiplying this by r^2t^2/s

$$mgr^2t^2 = 2mr^2s + 2Is\left(\frac{N+n}{N}\right)$$

Hence

$$I = mr^2\left(\frac{gt^2}{2s} - 1\right)\frac{N}{N+n} \tag{8.3}$$

8.1.3 Method

Attach the free end of the cord to the pin in the axle of the flywheel and wind around the axle 10 times. The length of the cord has been adjusted so that it detaches from the flywheel when the mass reaches the table top. (Check that this is the case.) In addition it has been arranged that the reference line on the flywheel coincides with the pointer when the mass detaches.

Measure the height s of the mass above the table. Release the mass and record the time t it takes to fall to the table and the number of further revolutions N made by the flywheel before coming to rest. Repeat these measurements six times. Finally measure the mass m (including the mass of the cord) and the radius r of the flywheel axle.

Having do so calculate what fractions of the initial potential energy of the system are converted into translational kinetic energy, rotational kinetic energy and work against friction.

8.2 Rolling Cylinders

8.2.1 Aim

To study the role of mass, radius and distribution of mass on the motion of cylinders down an inclined plane.

8.2.2 Theory

When a cylinder rolls down an inclined plane without slipping, no work is done against friction even though friction is present. (Friction is indeed necessary in order to make the cylinder roll instead of slipping.) The original potential energy that the cylinder possessed at the top of the incline is therefore converted into rotational and translational kinetic energy only. The situation appears to be more complicated than in Experiment 8.1 as we now have one body (the cylinder) which is undergoing both translational and rotational motion simultaneously. However, we can resolve the mo-

tion into two parts which can be treated separately, viz:

(i) translation of the centre of mass

(ii) rotation of the cylinder about an axis through its centre of mass.

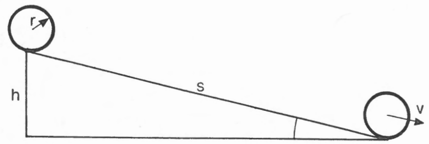


Figure 8-2

On rolling down the incline

decrease in PE = increase in KE(trans) + increase in KE(rot)

$$mgh = \frac{1}{2}mv^2 + \frac{1}{2}I\omega^2$$

and since $\omega = v/r$ this becomes

$$mgh = \frac{1}{2}mv^2 = \frac{1}{2}I\frac{v^2}{r^2}$$

or

$$mgh = \frac{1}{2}mv^2\left(1 + \frac{I}{mr^2}\right)$$

$$\text{and thus} \quad \frac{KE(trans)}{PE} = \frac{1}{(1+\frac{I}{mr^2})} \tag{8.4}$$

$$\frac{\frac{1}{2}mr^2}{mr^2}$$

(i) $I = \frac{1}{2}mr^2$ for a solid cylinder, and

(ii) $I = \frac{1}{2}mr^2\left[1+\left(\frac{r_i}{r}\right)^2\right]$ for a hollow cylinder.

where r = outer radius; r_i = inner radius.

Thus for solid cylinders the fraction of potential energy converted into translational kinetic energy should be 2/3, independent of the mass or radius of the cylinder. For hollow cylinders the fraction should be closer to 1/2.

$$\frac{\frac{1}{2}mr^2}{\frac{1}{2}mr^2}$$

8.2.3 Method

You are provided with four cylinders; three solid and one hollow. To investigate how mass, radius and distribution of mass affects the acceleration of the cylinders down the incline, begin by choosing the two solid cylinders of the same radii, and recording the time taken for each to roll down the incline. Take ten measurements for each cylinder and record the mean. Does the mass affect the acceleration?

Next select two of the solid cylinders with different radii, again timing each for 10 trips down the incline. Does the radius affect the acceleration?

Finally select one of the solid cylinders and the hollow cylinder and time 10 further traversals of the incline for each. Does the distribution of the mass affect the acceleration? None of your 10 measurements in each set should deviate by more than 0.2 s from their mean value. Discard any measurements showing larger deviations than this and make further measurements until you have a set of 10 which satisfies this requirement. Measure the distance s covered by the cylinders (remembering to subtract the diameter of the cylinders if necessary) and the height h of the incline.

8.2.4 Analysis

The final velocity of v of the cylinders is, for the same reasons as outlined in 7.1.2, given by $v = 2s/t$. Therefore the fraction of the potential energy converted into translational kinetic energy is given by

$$\frac{KE(trans)}{PE} = \frac{\frac{1}{2}mv^2}{mgh} = \frac{2s^2}{ght^2} \tag{8.5}$$

Determine this fraction for the various cylinders provided and compare the results with the theoretically predicted values (Eq.8.4)

$$\frac{1}{1+\left(1+\left(\frac{r_i}{r}\right)^2\right)}$$

massless spring ($m'=0$) $T = 2\pi\left(\sqrt{\frac{m}{k}}\right)$

here $m' \neq 0$ → $M = \frac{m'}{3} + m$ → $T = 2\pi\sqrt{\frac{M}{k}}$ To verify plot graph eg T vs $\sqrt{M}$ and calculate k from slope

Then determine k and Δk using least squares

p xxiii

3 readings of T for each mass $k = \frac{4\pi^2}{m^2}$ $(4\pi^2 m^{-2})$

$\frac{\Delta k}{k} = |-2| \frac{\Delta M}{M}$

Experiment 9

Simple Harmonic Motion (and least squares)

References:

Giancoli (3rd Ed) 11-3

Halliday, Resnick & Walker (4th Ed) 14-2, 14-3

Physic 1 Lab Manual: Data analysis (section 2.5)

Following the ‘pre-prac talk’ an exercise on least squares fitting will be handed out. This exercise should be completed and checked by your Demonstrator before you begin the experiment laid out below.

9.1 Aim

To investigate the relationship between the period of oscillation of a mass on a spring and the magnitude of the mass, to find a value for the force constant k, and to use the method of least squares to calculate the error of k.

9.2 Introduction

In Expt 1 the effect of adding different masses to a spring was investigated. The extension of the spring was given by Hooke’s Law

$$F = kx, \tag{9.1}$$

$T = 2\pi \frac{2\pi}{\sqrt{k}}\sqrt{M}$

where F is the applied force, x is the extension, and k is the force constant.

If the mass attached to the spring is displaced a small distance x from its equilibrium position and then released, it has a restoring force $F = -kx$ applied to it by the spring. The mass is found to undergo simple harmonic motion provided the amplitude is small. The period of oscillation, T, is given by

$$T = 2\pi\sqrt{(m/k)}$$

(For proof of this see lecture notes, or textbooks referred to above.) Thus if m is known, the force constant k can be determined by measuring T. In practice the mass of the spring may not be negligible and the fact that it is also oscillating affects the period of oscillation. However provided the mass m' of the spring is small compared with m, we can correct for this effect by replacing m by the effective mass M, given by

$$M = m + m'/3$$

The period is then given by

$$T = 2\pi\sqrt{(M/k)} \tag{9.2}$$

9.3 Apparatus

Spring suspended from a retort stand, cylinders of differing masses, a stopwatch and access to a triple beam balance.

9.4 Measurement of period of oscillation

Use the triple beam balances to determine the masses of the four cylinders, and the mass of the spring. By measuring the time taken for a number of oscillations, calculate the period of oscillation for each cylinder in turn, and plot a graph to verify the form of Eq. 9.3. Having verified the form of Eq. 9.3, use the graph to determine the force constant of the spring.

9.5 Calculating the uncertainty, Δk, using the method of least squares

The value obtained for k has a related uncertainty which is best calculated using the least squares method outlined in section 2.6 in the Introduction. Following the tables used in the exercise handed out at the beginning of the practical, set out the details of the calculation of Δk for your results. Use the PC's in the laboratory to check your answer.

Experiment 10

Vibrating String

References:

Giancoli (3rd Ed) 11-11

Halliday, Resnick & Walker (4th Ed) 17-13

10.1 Aim

To generate stationary transverse waves in a stretched string and to use these to measure the velocity of the waves and hence the mass per unit length of the string.

10.2 Introduction

Waves are generated in a string by a vibrator fed from a function generator (see figure below).

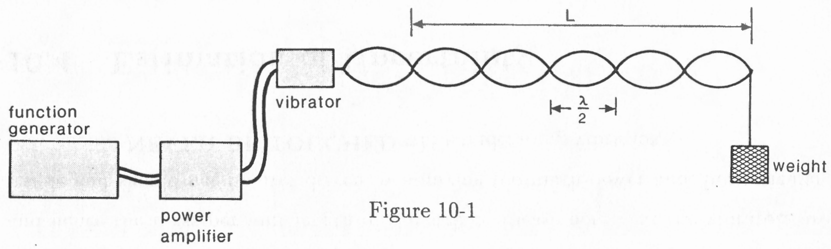


Figure 10-1

The frequency, f, of the waves, their wavelength, λ, and velocity, v, are related by the equation:

$$v = f\lambda \tag{10.1}$$

Since the string is effectively fixed at the right end, the travelling waves propagating along the string are reflected at this end and the reflected waves interfere with the forward travelling waves. At certain frequencies standing waves are produced and several nodes will be clearly visible. Since the distance between adjacent nodes is equal to half a wavelength (i.e. $\lambda/2$) it is therefore possible to determine the wavelength of the waves under these conditions. A plot of f vs $1/\lambda$ should give a straight line graph with slope v.

The velocity of the transverse waves is determined by the tension T in the string and the mass per unit length μ of the string viz.:

$$v = \sqrt{T/\mu} \tag{10.2}$$

Thus having found the velocity of the waves from the graph the mass per unit length of the string can be obtained from Eqn. 10.2 if T is known. Since the tension in the string is produced by the "weight" attached to the string, measuring its mass enables one to determine μ.

10.3 Method

Establish the mass of the "weight" using the triple beam balances. (As this need not necessarily be done at the beginning of the practical you may wish to delay this measurement until later if the queue for the balances is too large.)

Using the function generator coupled via the power amplifier to the vibrating unit to oscillate the string, find the frequency at which the string has 5 nodes. (Note: as the vibrating unit generates the waves in the string by oscillating the string up and down the left point at which the string is attached to the unit is not a node.) Measure the distance L between the extreme left and right hand nodes (see Fig 10-1) and hence obtain the wavelength of the waves. Increase the frequency and repeat the measurements at other standing wave positions until about 5 or 6 measurements have been made in the range from 5 nodes to about 15 nodes. Tabulate all the readings and plot a graph of f vs $1/\lambda$. From the slope of the graph find the velocity of the waves and hence the mass per unit length of the string. Please note that the vibrators are fragile and should not be over driven by applying too much power and, in particular, they should **NEVER BE TOUCHED** while undergoing vibration

10.4 Estimation of Uncertainty

It is always good practice when presenting a result to quote an estimation of the uncertainty associated with it. You are therefore required to estimate the uncertainty associated with your value for μ. The two sources of uncertainty in μ are the uncertainty of the slope of the graph (Δv) and the mass of the weight (Δm). The uncertainty in the graph can be estimated using the microcomputer. The uncertainty in T is probably best obtained from the least count of the laboratory scales. With the uncertainties of Δv and Δm and the table presented in Section 2.2.6 of the Introduction, obtain a value for $\Delta\mu$, the uncertainty in μ.

Experiment 11

Sound

References:

Giancoli (3rd Ed) 12-1, 4

Halliday, Resnick & Walker (4th Ed) 18-5

11.1 Speed of Sound

11.1.1 Aim

To measure the velocity of sound in an air column.

11.1.2 Theory

A loudspeaker sounded at one end of a long cylinder containing air causes sound waves to travel along the tube. These waves will be reflected at the far end, and the forward and reflected waves will interfere. For certain specific lengths of the air column when the two waves are in phase (i.e. peak of one corresponds to the peak of the other) a STANDING WAVE is produced. In this condition the air column is heard to RESONATE, producing a much louder sound of the same frequency as the loudspeaker. At resonance, points of zero displacement, called NODES, and of maximum displacement, called ANTINODES, are located along the air column. The loudspeaker is close to an ANTINODE, there being a small difference between its position and the antinode, called the 'end correction' (See Fig. 11-1).

In this experiment the cylinder is fitted with a movable plunger at which there is a NODE. If the length of the air column is increased from zero, the first critical length at which resonance occurs is $\lambda/4$. If the distance the plunger has moved is L_1, then:

$$\lambda/4 = L_1 + e \tag{11.1}$$

where e is the 'end' correction (see Fig. 11-1). As the plunger is moved further out, subsequent positions of resonance will occur where the length of the air column corresponds with $3\lambda/4$, $5\lambda/4$, etc. (See Fig. 11-1).

In each case the actual distance the plunger is moved L_2, L_3 etc. is less than these values by e. i.e.

$$3\lambda/4 = L_2 + e \tag{11.2}$$
$$5\lambda/4 = L_3 + e \tag{11.3}$$

etc.

The effect of the end correction can thus be eliminated by subtracting (11.2) from (11.1), (11.3) from (11.2), etc., yielding equations:

$$L_2 - L_1 = \lambda/2$$
$$L_3 - L_2 = \lambda/2 \tag{11.4}$$

etc. from which the wavelength λ is calculated.

The speed of sound V is related to the wavelength λ and to the frequency f. V is found by experiment to depend upon the absolute temperature T of the air column so we write

$$V_T = f\lambda$$

Thus with the calculated values of λ and the values of f read from the audio generator supplying the loudspeaker, V_T can be calculated.

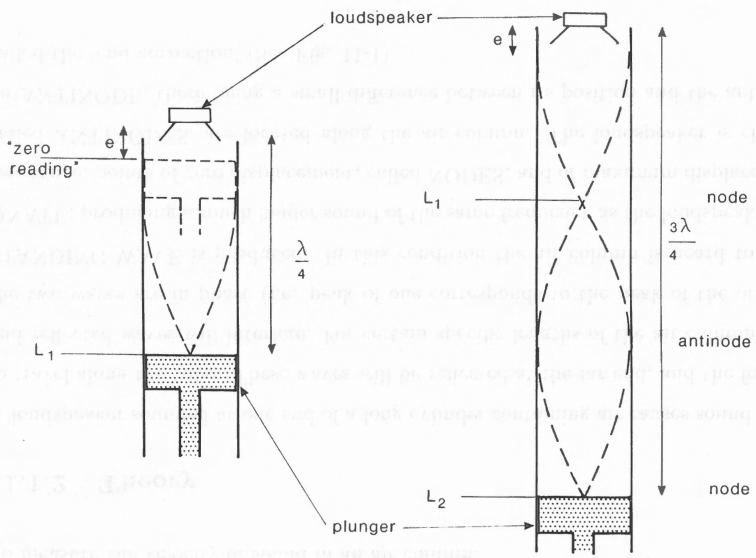


Figure 11-1

V_T, however is the speed of sound in the laboratory on the day on which you are doing the experiment. It is important to know the speed of sound at the standard temperature 0^o, and this can be found in the following way.

The speed of sound in a gas is related to the elastic properties of the gas, from which it can be shown that:

V_T	$=$	$\sqrt{\gamma RT}$	where
γ	$=$	$\frac{C_p}{C_v}$,	the ratio of the specific heats at constant pressure and at constant volume.
R	$=$		the universal gas constant.
T	$=$		the absolute temperature.

Thus we can relate the speeds of sound at two different temperatures.

	V_{T_2}/V_{T_1}	$=$	$\sqrt{T_2/T_1}$
or	V_o/V_T	$=$	$\sqrt{273/T}$
therefore	V_o	$=$	$V_T\sqrt{273/T}$
where	V_o	$=$	speed of sound at 0^oC (273 K)
	V_T	$=$	speed of sound at T K.

11.1.3 Apparatus

A PVC tube, mounted horizontally is fitted on one end with a loudspeaker and at the other with a wooden plunger attached to a rod. The rod carries a pointer which travels along a metre scale providing a means of reading the plunger's position. The loudspeaker is driven by a variable frequency audio oscillator.

11.1.4 Method. Finding the Velocity of Sound at 0^oC.

Set the oscillator frequency to a value in the range from 400 to 600 Hz. Find and record the positions of the plunger at resonance over the full cylinder length. Repeat this series of readings for at least 2 other frequencies in the same range.

NOTE:

- KEEP THE INTENSITY OF THE SOUND LOW AT ALL TIMES. At high intensities the loudspeaker may oscillate at multiples of the applied frequency and this may mask or 'smear out' the resonance positions. Also, your ear is more sensitive to intensity changes of low-intensity sounds.
- The temperature in the laboratory may drop about 6^oC during the afternoon. You should thus read the temperature just before you start the experiment and immediately after your last readings are taken. Use the mean value in your calculations.

Tabulate all the readings of oscillator frequency and plunger positions. Include in your table columns for the wavelength and velocity of sound V at temperature T K. Hence calculate V_o, and estimate its uncertainty.

11.2 Tuning fork

11.2.1 Aim

To measure the frequency of a Tuning fork using a Stroboscope.

11.2.2 Introduction

A tuning fork is a mechanical vibrator which, when sounded by striking lightly on a rubber bung, vibrates at a single frequency and emits a sound wave. The frequency of this mechanical vibrator can be established using a STROBOSCOPE, which provides calibrated flashing light source. The frequency of the stroboscope can be adjusted so that its frequency bears a direct relationship to that of the tuning fork. The following discussion illustrates by example how this relationship can be understood:

(i) If the stroboscope frequency is exactly that of the fork, the light flashes each time the blades of the fork are in the same position. Hence the observer sees the tuning fork as stationary. We say a stationary pattern is observed.

(ii) If the strobe frequency is twice that of the fork, the light illuminates the fork twice in each cycle, so the blades of the fork would be observed at two different points of its motion. We would observe a 'double' pattern.

(iii) If the strobe frequency is half that of the fork, the light shines once every two cycles. As in (i), a stationary pattern is observed.

The strobe frequency range is from 0 to 250 Hz (15000 r.p.m.) whereas the tuning fork frequency is about 300 Hz. Thus the strobe frequency required to produce a stationary (single) pattern will be some sub-multiple of the tuning fork frequency as in (iii).

11.2.3 Method

To establish the tuning fork frequency, you must obtain a series of frequencies at which stationary patterns are observed. It is important that the frequencies are consecutive,

so after finding the first stationary pattern, adjust the frequency slowly in order not to miss a stationary pattern. (Your demonstrator will explain this point.) Start with the highest frequency of the stroboscope and work towards the lower frequencies. From the series of frequencies of the stationary patterns the tuning fork frequency is determined by multiplyig the strobe frequencies by integers to arrive at a lowest common multiple. The integral multipliers are found by trial. The following example illustrates the method:

Strobe frequency readings	9580	6390	4780	3830	r.p.m.
Trial integral multipliers	2	3	4	5	
Tuning fork frequency	19160	19170	19120	19150	r.p.m.

Thus the average frequency is : 19150 r.p.m. = 319.2 Hz.

11.2.4 Apparatus and Experimental Procedure

A calibrated stroboscope, tuning fork and rubber bung are provided. (Check carefully the units of the stroboscope, and the ranges of the scales.) Set the tuning fork oscillating by LIGHTLY striking it on the rubber bung. Hold the vibrating fork in the flashing light, ensuring that you do not look directly into the Xenon flash tube, and find the frequency of the first stationary pattern. By slow adjustment of the stroboscope frequency find the other frequencies that give stationary patterns. Tabulate the results, calculate the tuning fork frequency and estimate the uncertainty.

Experiment 12

Coupled Oscillators

References:

A.P. French: Vibrations and Waves Chapter 5

H.J. Pain: The Physics of Vibrations and Waves Chapter 3

12.1 Aim:

To investigate the motion of two coupled oscillators, relating it to the concept of normal modes.

12.2 Introduction

Many physical systems can be analysed by treating them as a set of harmonic oscillators coupled together in some way. As an introduction to this important subject you will be investigating the simplest such case: two oscillators coupled by a Hooke's law force. A fundamental concept will emerge: any state of motion of the system can be regarded as a superposition of "normal mode" motions.

In the theory section below, an important relation (Eq.12.4) connecting certain characteristic frequencies of the system is derived. You will make measurements to test this relation, and to test your experimental skill! In a theoretical exercise you are asked to

derive two relations between the force constants of the springs. Again you will make measurements to test these relations.

Coupled oscillators are important because of the range of phenomena that can be explained in terms of the elegant theory. They are also fun; getting coupled oscillators into their various modes of motion, and watching the motion, is an enjoyable activity.

Enjoy yourself!

12.3 Theory

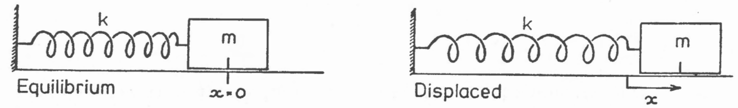


Fig. 12-1

If the mass m in the single oscillator above is displaced horizontally from its equilibrium position ($x = 0$) and then released, it will perform simple harmonic motion (SHM) of angular frequency $\omega_0 = \sqrt{k/m}$, k being the spring constant. The position x at time t will be given by $x = A\cos(\omega_0 t + \phi)$, where A is the amplitude and ϕ is a phase angle which specifies the initial position of the mass. We frequently choose the case $x = A$ at $t = 0$ to make ϕ zero. (Remember that angular frequency $= 2\pi\times$ frequency $= 2\pi$ /period i.e. $= 2\pi\nu = 2\pi/T$.

Now let us couple two such oscillators by a third spring, with spring constant k'.

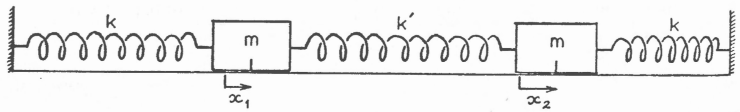


Fig. 12-2

If one oscillator is displaced from its equilibrium position and released, the two masses are observed to have the motions represented below. Energy is transferred periodically

from one oscillator to the other.

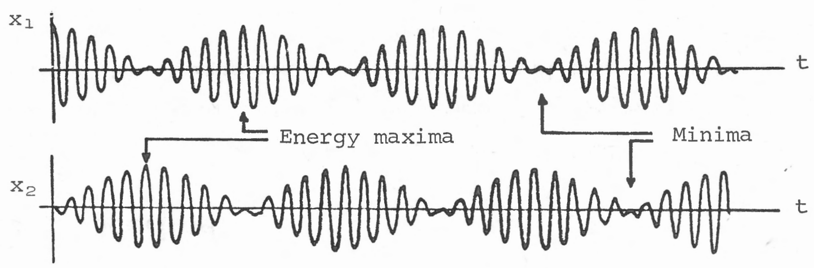


Fig. 12-3

These are not simple harmonic motions because the amplitudes are not constant. We can however, easily relate this type of motion to SHM by the following procedure.

Suppose we add two SHM's of frequencies ω_f and ω_s, which are slightly different, but whose amplitudes are identical and equal to A.

$$A\cos\omega_f t + A\cos\omega_s t = 2A\cos\left[(\omega_f-\omega_s)t/2\right]\cos\left[(\omega_f+\omega_s)t/2\right] \qquad (12.1)$$

This gives a pattern identical to that in the upper sketch above: a harmonic oscillation at frequency $(\omega_f+\omega_s)/2$, modulated by a slower harmonic vibration at frequency $(\omega_f-\omega_s)/2$. If you like you can think of $2A\cos\left[(\omega_f-\omega_s)t/2\right]$ as a time dependent amplitude.

The question now is whether the two SHM's $\cos\omega_f t$ and $\cos\omega_s t$ have any physical reality with relation to our system. In other words, can we find two ways of setting our system in motion so that all parts of it describe SHM at the angular frequency ω_f or ω_s? These unmodulated SHM's are called the "normal modes" of the system. Any other state of the system can be considered to be a linear superposition of the normal modes, i.e. we just add together normal mode motions with appropriate amplitudes and phases. Our initial task is therefore to establish what the two normal modes will be.

One of the normal modes of our system is easy to visualise. Suppose that both masses are given equal displacements in the same direction. The coupling spring k' will remain

at its equilibrium length; we could conceptually replace it by a light rigid rod. When the two masses are released simultaneously from their displaced positions they will perform SHM's in phase just as if the coupling spring were not present. The angular frequency will be the same as that of a single oscillator, i.e. k/m. Call this the "s" mode.

$$\omega_s = \sqrt{k/m} \qquad (12.2)$$

The other normal mode can be excited by releasing the two masses from initial displacements which are equal in amplitude but opposite in direction. The two masses now perform SHM's which are out of phase. The frequency of this normal mode will be greater than that of the in-phase mode because the coupling spring provides an additional restoring force. In fact since the change in length of the coupling spring is just double that of either of the other two springs, the restoring force becomes $(k+2k')x$, instead of kx, giving the mode frequency

$$\omega_f = \sqrt{(k+2k')/m} \qquad (12.3)$$

The meaning of the subscripts f and s is now revealed: f = fast, s = slow.

We have now identified the two normal modes of the system: a slow mode with the two masses moving in phase, and a fast mode with the masses moving out of phase.

When a system is in a mixed mode, the most prominent feature of the motion is the periodic exchange of energy between the two oscillators. The frequency at which this occurs is readily related to the mode frequencies, as seen in the superposition represented below.

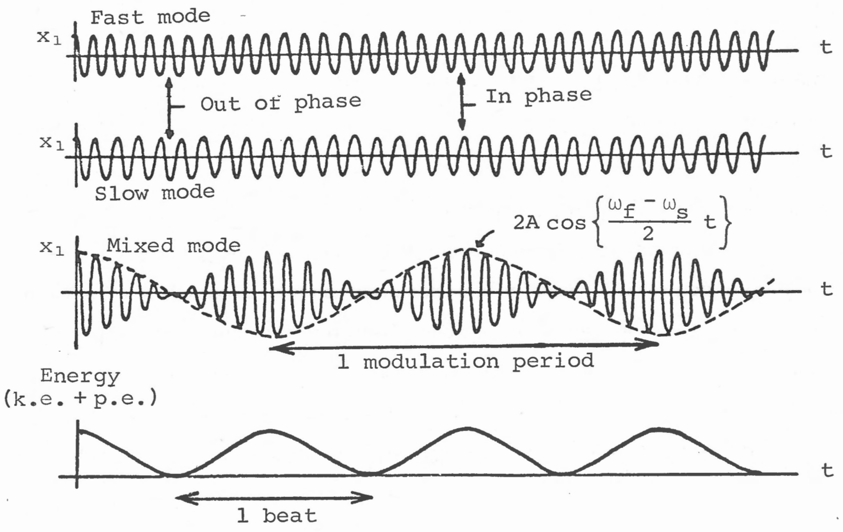


Fig. 12-4

The angular frequency of the amplitude modulation function is $(\omega_f - \omega_s)/2$. The energy of an oscillator is proportional to the square of the amplitude, which results in a periodic energy function with an angular frequency double that of the amplitude modulation function, i.e. $\omega_b = \omega_f - \omega_s$. Dividing by 2π to get this in terms of frequencies

$$\nu_b = \nu_f - \nu_s \tag{12.4}$$

The frequency is known as the beat frequency.

12.4 Method

The oscillators you will use are mass-spring systems, the masses being supported on the air cushion of an air track to minimise frictional forces. Remember that the air tracks and gliders are precision devices; handle them with care. Do not detach the springs or remove the gliders from the air tracks.

Timing of the various oscillation periods will be done with a stop watch. In determining the periods, you should time 10 complete oscillations a number of times, we suggest 5 times. From these measurements, you can then determine a mean period and standard deviation, and hence obtain a mean frequency and standard deviation.

Now proceed with the practical as described below.

1. Get the oscillators moving in a mixed mode by giving one mass a horizontal push, or by releasing both masses simultaneously, one from its equilibrium position, the other from a displaced position. Obviously you should restrict the amplitudes to reasonable values so that the springs remain in tension. Observe the periodic transfer of energy from one oscillator to the other. Determine the beat frequency ν_b. (Remember that one beat is the time between successive overall minima of the motion.)

2. Practise getting the system into its normal modes. This requires some care - try to make the initial displacements exactly equal, and to release the masses simultaneously. The amplitudes should stay constant, apart from the slow damping due to air resistance etc. Determine the frequencies ν_s and ν_f of the two normal modes. Calculate the difference $(\nu_f - \nu_s)$ and the standard deviation in this quantity.

3. To test Eq.12.4, compare your values of ν_b and $(\nu_f - \nu_s)$. Because of the uncertainty associated with each of the readings it is highly unlikely that the two values agree exactly. There is, however, a 95% probability of the true value of ν_b being within the range $\bar{\nu}_b \pm 2\sigma_b$. Similarly for the value of $(\nu_f - \nu_s)$. If there is any overlap between these two ranges we say that there is *agreement within experimental uncertainty.* If your values of ν_b and $(\nu_f - \nu_s)$ do not agree, your experimental technique may be at fault. Make sure that you are getting the system into pure normal modes and repeat a few measurements. Check your calculations.

4. Finally, investigate the behaviour of two non-identical coupled oscillators. The easiest way to do this is to add an additional mass (50 to 100 g) to one oscillator. Use a handy object - keys, calculator, whatever. Sketch the amplitude of one oscillator after giving one of the masses an initial displacement. Does it make any difference whether the heavier or the lighter mass is given the initial displacement?

$\Delta r = 0.05 mm$

Experiment 13

Viscosity

References:

Giancoli (3rd Ed) 10-10,12
Halliday, Resnick & Walker (4th Ed) 6-3

13.1 Aim

To measure the viscosity of a "thick" oil, using a dropping ball technique.

13.2 Apparatus

Measuring cylinder containing oil (density 969 kg m^{-3}), Ball bearings (density 7780 kg m^{-3}), Timer, Metre-stick, micrometer screw gauge.

13.3 Introduction and theory

The study of the movement of liquids along tubes of varying diameter is a matter for engineers and doctors alike. Engineers are concerned with the hydraulic control of machinery, and doctors with the flow of blood in arteries. The flow of fluids is well described by the laws of hydrodynamics with the equations of Continuity, Bernoulli and Poiseuille (see references for discussion of these equations). A property of all fluids which has to be taken into account is the VISCOSITY which is defined as the amount

of internal friction of a fluid, i.e. viscosity is the frictional force between layers of molecules in a fluid and is caused by the cohesive forces between molecules.

To characterise a liquid's viscosity a "coefficient of viscosity" η is defined from the consideration of the force F required to move two plates of area A across one another at a velocity v when separated by a layer of liquid of thickness ℓ.

Experiment has shown that

$$F \,\alpha\, \frac{v}{\ell} \times A$$

$$\text{Hence write } F = \eta \frac{vA}{\ell}$$

$$\text{Then } \eta = \frac{F\,\ell}{A\,v}\; Pa\,s\; (N s\, m^{-2})$$

The viscosity η is very sensitive to temperature.

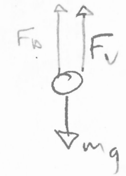
To measure η, we shall uses a static fluid with an object falling through the fluid. This is called the "Falling Ball" technique and is the basis of all sedimentation studies. "Falling ball" viscometers are used in many industrial laboratories.

13.3.1 Falling ball technique

For an object falling in a fluid three forces are acting: (i) the weight mg, (ii) the buoyant force F_B (= weight of fluid displaced), and (iii) the viscous drag force F_v.

Newton's 2nd Law gives $\Sigma F_{ext} = ma$, i.e.

$$mg - F_B - F_v = ma \tag{13.1}$$



$$\text{Now } F_B = \rho_f V g$$

where ρ_f = density of fluid and V = volume of object, while

$$mg = \rho_o V g$$

where ρ_o = density of object.

The viscous drag is given by $F_v = 6\pi\eta r v$ which is Stokes' equation for the case of laminar (non-turbulent) flow which will apply in this experiment. (r = radius of the ball)

It is found that in a viscous medium the solid object reaches a maximum steady speed because the drag force F_v increases with v until it reaches a value such that ΣF_{ext} are zero, and hence acceleration is zero. This speed is called the "terminal velocity" v_T.

$= \frac{2(\rho_o - \rho_f) g r^2}{9 v_t}$

Equation 13.1 now becomes $\rho_o V g = \rho_f V g + 6\pi\eta r v_T$

$$\text{i.e. } \eta = \frac{(\rho_o - \rho_f)Vg}{6\pi\, r\, v_T} \quad \text{with } V_{sphere} = \frac{4}{3}\pi r^3 \tag{13.2}$$

By measuring v_T and r, η can be determined provided the densities are known. Substituting for V in Eqn 13.2 gives

$$\eta = \underbrace{\frac{2(\rho_o - \rho_f)g}{9}}_{\text{constants}} \frac{r^2}{v_T} \tag{13.3}$$

$v_T = \frac{2(\rho_o - \rho_f) g r^2}{9\eta}$

13.4 Method

6 distances × 3 times

Equation 13.3 shows that η can be evaluated by obtaining a value for v_T for a ball of radius r, measured with the micrometer. To obtain a reliable value of v_T, the falling ball is timed over a number of different distances. Instead of re-using the same ball, a number of identical ball bearings are provided. Each ball should be timed between 2 graduations on the measuring cylinder. The ball travels a short distance before reaching its terminal velocity. Hence the top mark must be 30-40 cm below the liquids' surface. Drop the balls through the hole situated centrally in the cylinder cover, timing each one as it falls a particular distance. Time 3 balls for each of 5 or 6 different distances. Measure the distances between the graduation marks you used, and the ball's diameter. Record all the data in a table, plot the appropriate graph to obtain v_T and hence calculate η. Calculate also the uncertainty in your result using the microcomputer if necessary.

1-10
11-20
21-30

3,5 mm

d(cm)	t(sec)	t_2	t_3	Average

slope = v_t

$\Delta\eta = \eta\sqrt{\left(\frac{2\Delta v_t}{v_t}\right)^2 + \left(\frac{\Delta r}{r}\right)^2}$

Experiment 14

Gas Laws

References:

Giancoli (3rd Ed) 13-5

Halliday, Resnick & Walker (4th Ed) 19-4

14.1 Boyle's Law

14.1.1 Aim

To verify Boyle's law for air.

14.1.2 Introduction

Boyle's law states that for a given mass of gas, at constant temperature, pressure is inversely proportional to volume for a perfect gas. The apparatus provided is illustrated in Fig. 14-1 below.

A sample of air is contained in a glass tube of uniform cross-sectional area, between a tap and a column of oil. The glass tube is graduated in units of volume. The pressure of the air sample in the glass tube can be varied by pumping the bicycle pump. The pressure inside the air sample is read on the dial gauge which reads the pressure above atmospheric pressure.

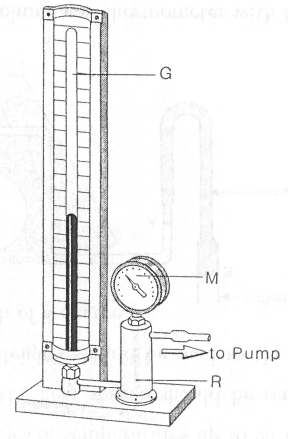


Figure 14-1

14.1.3 Method

Ensure that initially the pressure on the oil is zero by checking the dial gauge. (If necessary open the valve to bring it to zero.) Read the volume of air from the graduated column, and the pressure on the gauge P_G. Increase the pressure on the air column by pumping the bicycle pump. (DO NOT BE TOO VIGOROUS.) Again read the volume and pressure P_G. Repeat for a number of different pressures, taking sufficient readings to be able to plot a good graph of pressure against 1/volume. Read the atmospheric pressure P_{at} (in mm Hg) on the Fortin Barometer, and convert it to kilopascals: (kPa).

14.1.4 Analysis

For each set of readings calculate the pressure $p = P_{at} + P_G$. Plot a graph of pressure against 1/(volume). If this is found to produce a straight line then pressure is inversely proportional to volume. Boyle's law will thus have been verified if a straight line graph is obtained.

14.2 The constant-volume gas thermometer

14.2.1 Aim

To verify Gay-Lussac's law and to determine the Celsius temperature of absolute zero.

14.2.2 Introduction

Gay-Lussac's law states that for a perfect gas, at constant volume, the gas pressure is proportional to the Absolute temperature of the gas i.e. $p \alpha \theta$ (Absolute). A plot of pressure p versus θ(Absolute) will therefore produce a straight line passing through the origin as shown in Fig 14-2 below.

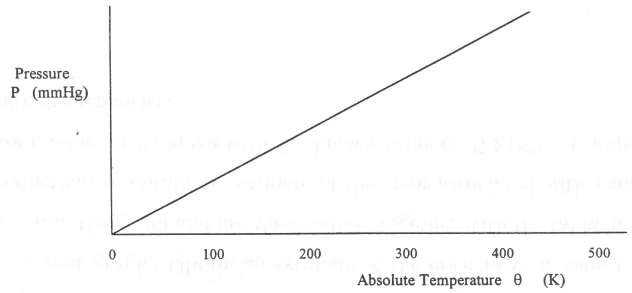


Figure 14-2

If instead of plotting p against the Absolute temperature, it is plotted against the Celsius temperature, θ, the intercept of the y−axis with the x−axis 'shifts' along the x−axis as shown in Fig 14-3 below.

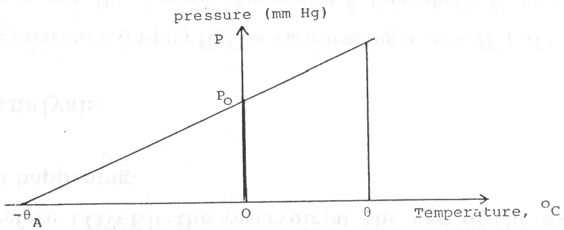


Figure 14-3

The straight line now no longer passes through the origin, but intercepts the y−axis at some positive value, say p_0, and intercepts the x−axis at some negative value, say -θ_A. (θ_A is thus the Absolute temperature corresponding to a Celsius temperature of 0^oC.)

The equation describing the relationship between p and θ is therefore of the general straight-line form, namely $p = m\theta + c$. By referring to Fig 14-3 it can be easily seen that the intercept $c = p_0$ and slope $m = p_0/\theta_A$. The precise relationship between p and θ is therefore given by the equation:

$$p = (p_0/\theta_A)\theta + p_0 \tag{14.1}$$

In this experiment, air is assumed to be a perfect gas, and p is measured as a function of θ, over the range 0 to 90°C, whilst volume is kept constant. θ_A can then be found from Eq. 14.1 or determined graphically.

14.2.3 Method

Completely surround the bulb with ice as shown in Fig. 14.4, then adjust the movable limb so that the mercury height A is at some convenient point. Continue to adjust until the levels no longer change, then record heights A and B. Replace the ice with water at room temperature, then raise the movable limb so that height A returns to the same position. Record height B, and the temperature, θ, as measured by a mercury-in-glass thermometer. Repeat for a series of temperatures up to 90°C at about 10°C intervals. In the interests of accuracy, the heat source should be removed and the water well stirred before each reading. Heights should be read to the nearest millimeter, and θ should be estimated to a tenth of a degree.

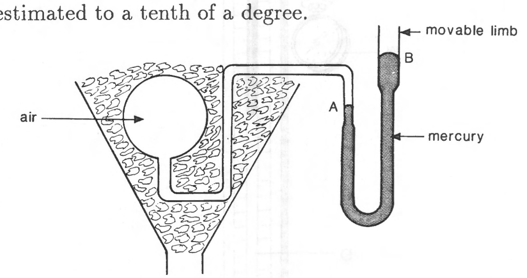


Fig. 14-4 Constant-volume gas thermometer with bulb in ice funnel.

PLEASE NOTE. The gas contracts as it cools. If the apparatus is left unchanged after taking the 90°C measurement the contraction of the gas will result in mercury being sucked into the bulb of the thermometer, which is difficult to fully remove. **You should therefore LOWER the reservoir at the end of the experiment to prevent this happening.**

14.2.4 Analysis

Calculate the pressure p (in mm Hg) for each reading as $p = H + B - A$ where H is atmospheric pressure. Plot a graph of p against θ, then obtain θ_A by noting that Eq. 14.3 indicates that your graph should have a slope of p_0/θ_A. It is tempting to plot your temperature range from -300°C to +100°C in order to read off θ_A directly from the intercept with the temperature axis. This however results in all your data appearing in the top right hand corner and thus gives rise to considerable inaccuracy. It is therefore much better to plot temperature over the range 0 to 100°C and then to calculate θ_A from the slope of your graph. Obtain an estimate of the error in your values for the slope and intercept of the graph and use these values, together with the table in section 2.7 of the Introduction, to obtain an estimate of the error associated with your value for θ_A. Does your value for θ_A agree with the known value of 273.18°C? Comment on the source of any discrepancies.

Experiment 15

Thermal Conductivity

References:

Giancoli (3rd Ed) 14-7

Halliday, Resnick & Walker (4th Ed) 20-7

15.1 Aim

To measure the thermal conductivity of a poor conductor.

15.2 Introduction and theory

The rate of flow of heat, Q/t, through the slab of material shown (Fig. 15.1) is given by:

$$Q/t = KA(T - T')/d \tag{15.1}$$

where heat Q flows in time t, K is the thermal conductivity of the material, A the cross-sectional area, d the thickness of the slab, and $T - T'$ is the temperature difference between the faces.

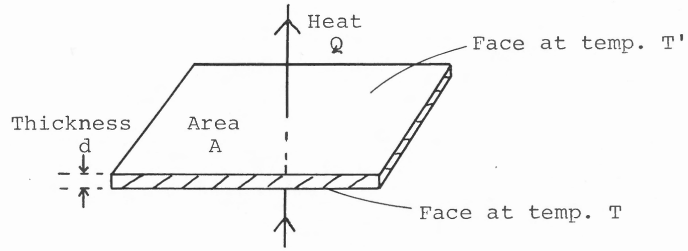


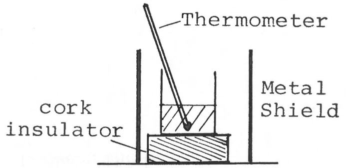
Fig. 15-1

In this experiment, one side of a specimen slab is heated by steam whilst the other side is in contact with a copper calorimeter containing water (Fig. 15.3). The rate of flow of heat from the steam heater to the calorimeter is deduced from the temperature rise of the water in the calorimeter. Compensation for the significant loss of heat from the calorimeter and its contents to the surroundings is achieved by a graphical method relying on Newton's law of cooling (the rate of cooling is proportional to the difference in temperature between the calorimeter and its surroundings).

15.3 Method

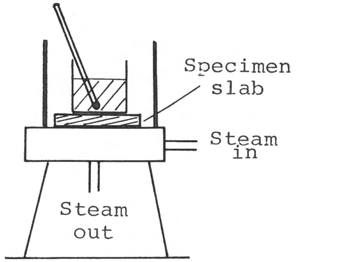
Fill the steam boiler with water to the top of the glass gauge. Attach the rubber tubing from the boiler to the side inlet of the steam heater and begin heating the water. Find the cross-sectional area of the calorimeter base A, the thickness of the specimen slab d, and the mass of the empty, dry calorimeter. Half fill the calorimeter with water, remeasure the mass and hence determine the mass of the water in the calorimeter . Place the specimen slab on the steam heater to get thoroughly warmed. Place the calorimeter with water, plus a 50°C thermometer on the large insulating cork and surround with the metal shield as shown in Fig. 15.2. Take temperatures every minute for four or five minutes, remembering to stir well before each reading. Now place the calorimeter on the slab and apply heat as shown in Fig. 15.3. Continue stirring and taking temperatures every minute until the temperature has risen by 10 to 15 degrees. Remove the calorimeter and allow it to cool under its original conditions (Fig. 15.2).

Continue taking readings for about 10 minutes.



Cork insulator + calorimeter as used before and after heating.

Fig. 15-2



Calorimeter and bad conductor on steam heater.

Fig. 15-3

15.4 Analysis

Plot a graph of temperature against time and correct for heat losses from the calorimeter by means of the construction shown in Fig. 15.4.

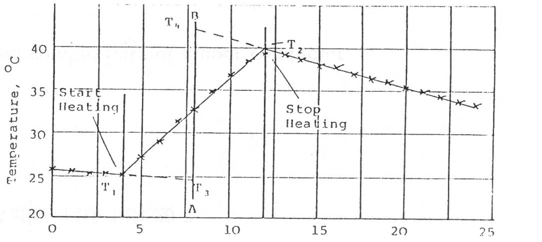


Fig. 15-4

The actual temperature rise is $T_2 - T_1$ while the corrected rise is $T_4 - T_3$. The vertical line AB is drawn at the mid point of the heating period. Calculate Q from:

$$Q = (m_1 c_1 + m_2 c_2)(T_4 - T_3) \tag{15.2}$$

where m_1 and m_2 are the masses of the calorimeter and water, c_1 is the specific heat of copper (393 J kg^{-1} °C^{-1}) and c_2 is the specific heat of water (4186 J kg^{-1} °C^{-1}). Having obtained Q the thermal conductivity of the slab, K, can now be calculated from Eq.15-1 where A is the cross-sectional area of the calorimeter (why the calorimeter and not the slab?), T is the temperature of saturated steam (obtained from graphs in the

laboratory next to the Fortin barometers) and T' is the average temperature of the calorimeter during the heating cycle, ie;

$$T' = (T_1 + T_2)/2 \tag{15.3}$$

Consider possible sources of error, and decide which of the measured variables in Eq. 15-1 and Eq. 15-2 are likely to have the largest percentage uncertainty. Use this information to obtain a rough estimate of the uncertainty in your value of K.

QUESTION: What justification can you give for the construction used to correct for heat losses?

Experiment 16

Ohmic and Non-Ohmic Conductors

References:
Giancoli (3rd Ed) 18-2,3
Halliday, Resnick & Walker (4th Ed) 28-1,2,4,5

16.1 Aim

To investigate the relationship between current I and potential difference V for two electric circuit elements carrying direct currents.

16.1.1 Theory

An electric current I is a flow of charge, and a direct current (DC) implies a flow in one direction. The power source for direct currents can be a battery, either a dry cell of a lead accumulator or a 'power supply' working off the mains plug. The unit of electric current is the *ampere*.

To initiate and maintain a current in a conductor an electrical 'pressure' has to be established across the ends of the conductor. The electrical pressure is called the *potential difference*, V, and is measured in *volts*.

A useful analogy to clarify these ideas is the flow of water in a pipe. For water to flow, the pressure at one end of the pipe must be 'higher' than at the other. This pressure difference is analogous to the electrical potential difference across a conductor, and the

amount of water passing per second is analogous to the electric current. Here the power supply or the electrical battery is replaced by a mechanical pump which maintains the pressure difference between the ends of the pipe.

When an electric current flows in a conductor, charge carriers move through the material and interact with the constituent atoms, impeding the flow. This phenomenon is called electrical resistance, R, and is measured as the ratio:

$$\text{Resistance} = (\text{Potential difference})/\text{Current}$$

$$\text{or } R = V/I \tag{16.1}$$

The unit of resistance is the *ohm* = volt/ampere

As the potential difference V across a conductor is varied, the current I will also vary. In this experiment the variation of I with V will be studied for three circuit elements. This variation is not expected to be the same for all conducting circuit elements. There are two categories:

(1) LINEAR or OHMIC elements. For these elements the ratio V/I is constant, and the resistance obeys Ohm's Law, i.e. $R = V/I$ = constant for all V. This is best verified by plotting values of I against V. The resultant graph will be a straight line through the origin and the slope of this line gives the reciprocal of the resistance, R.

(2) NON-LINEAR or NON-OHMIC elements. The ratio of V/I for these elements is not constant, and a plot of I against V yields graphs of varying shapes. The resistance is still calculated from the ratio V/I for particular values of V. The shape of the I vs. V graph is described by another parameter, the slope resistance, which is the reciprocal of the gradient of the tangent $\Delta I/\Delta V$ to the curve.

$$\text{slope resistance} = \Delta V/\Delta I = 1/(\Delta I/\Delta V)$$

Note: As the graph is a plot of I vs. V, I is on the vertical axis, V on the horizontal axis. The slope of the graph will thus yield $\Delta I/\Delta V$.

16.2 Apparatus and Method

The two circuit elements to be investigated are:

(1) a carbon resistor

(2) a light bulb

To measure the voltage and current suitable meters are provided. The power source is fed to the circuit via a rheostat to allow one to vary the voltage. A slightly larger voltage source is requird for the light bulb. The circuits to be used is shown in Fig. 16-1.

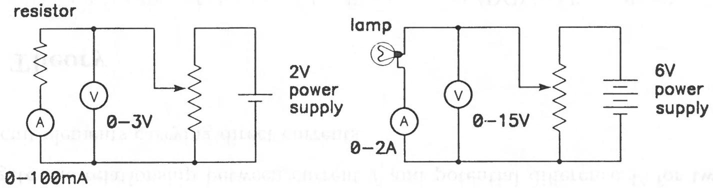


Fig. 16-1

HAVE THE CIRCUIT CHECKED BY A DEMONSTRATOR BEFORE PROCEEDING.

Take measurements of the current and voltage at suitable intervals over the fullest range for each circuit element. Reverse the polarity of the elements so that readings are obtained for current travelling through the element in both directions. Denote the one direction +ve, the other -ve. Tabulate the data, and calculate the resistance for each pair of readings. Plot graphs of I (dependent variable) against V (independent variable) for each element using the same axes where possible, providing positive and negative axes in each case.

From the graphs find the resistance and slope resistance for the resistor and the light bulb at 0.5 and 1.0 volts. From the results decide to which category of conductor (Ohmic or Non-ohmic) each element belongs.

Experiment 17

Introduction to the oscilloscope

References:

Physics 1 Lab Manual - Appendix D

17.1 Aim

The aim of this experiment is to become familiar with the cathode ray oscilloscope. Having mastered the oscilloscope it is to be used to determine the effective resistance of series and parallel combinations of resistors.

17.2 Introduction

The oscilloscope has been used by scientists and engineers for many years and it is now finding increasing use and application in biology and medicine. A general description of the various components of the oscilloscope and their role is given in Appendix D of this manual. Students should read this appendix before attending this practical. Once at the practical students should ensure that they are able to:

(i) switch on the oscilloscope, adjust the brightness and focus the trace,

(ii) alter the position of the vertical and horizontal trace,

(iii) alter the vertical and horizontal scale of the signal and to set the oscilloscope in the "calibrate" mode, and

(iv) to switch between the ac and dc modes.

This is probably best done by connecting the oscilloscope leads to the output of the signal generator and observing the signal obtained. Ensure that you are able to use the oscilloscope to measure the peak-to-peak voltage of the signal as well as the frequency of the signal. (In order to do this it is necessary to set the time base and voltage base of the oscilloscope into the "calibrated" modes.) The signal generator has three "frequency" and two "power" settings. Use the oscilloscope to measure the frequency and the peak-to-peak voltage for each setting. Record your readings in your practical book.

17.3 Series combination of resistors

Having familiarized yourself with the oscilloscope your next task is to measure the effective resistance of a series combination of two resistors, R_1 and R_2. Connect the two resistors R_1 and R_2. in series with the standard resistor R_s (whose value is given on the box) and then connect the whole combination to the signal generator as shown in Figure 17-1 below. Choose the frequency and power settings of the signal generator you feel would be most convenient and stick to these settings throughout the rest of the practical.

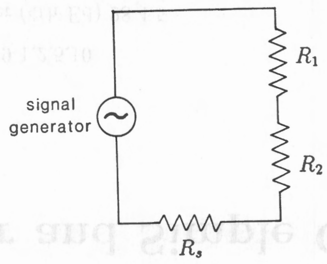


Figure 17-1 Series combination of R_1 and R_2.

The first task is to determine the value of R_1 and R_2. Since the oscilloscope only measures voltage (and frequency) it is necessary to know the current in the circuit in order to determine the values of the two unknown resistors. This is achieved by using

the oscilloscope to measure the voltage across the known standard resistor, R_s. The current, I, in the circuit can then be found from $I = V_s/R_s$. Having determined I the value of the R_1 and R_2 can be found by measuring the voltage across each resistor individually (ie across ab and across bc). To determine the effective resistance of a series combination of R_1 and R_2 measure the voltage across the $R_1 - R_2$ combination (ie across ac) and use your known value of I to determine R_{ef} (ie $R_{ef} = V_{ac}/I$). Compare your value of R_{ef} with the predicted value given by $R_{ef} = R_1 + R_2$.

17.4 Parallel combination of resistors

Next connect R_1 and R_2 in parallel and then connect the parallel combination in series with R_s as shown in Figure 17-2 below.

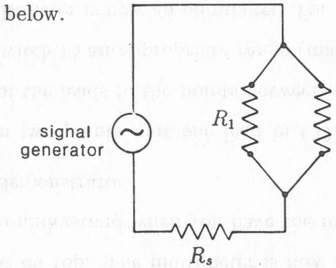


Figure 17-2 Parallel combination of R_1 and R_2.

Again determine the current through the circuit by measuring the voltage across R_s. Then measure the voltage across the parallel combination, V_{ac}, and hence determine the effective resistance of the parallel combination from $R_{ef} = V_{ac}/I$. Compare your measured value for R_{ef} to that predicted by the equation:

$$1/R_{ef} = 1/R_1 + 1/R_2.$$

This practical has deliberately been kept short in order to allow plenty of time to "play around" with the oscilloscope. Try using the other channel. You could also borrow a pair of leads from your neighbour in order to display two signals and then add the signals.

Experiment 18

Multimeter and Simple Circuits

References:

Giancoli (3rd Ed) 18-2,3 19-1,2,5,10

Halliday, Resnick & Walker (4th Ed) 28-4,5

18.1 Introduction

This experiment is designed as an introduction to the concepts that you need to understand simple electrical circuits: current, voltage, resistance, Ohm's Law, series and parallel circuits. You will use a digital multimeter as a voltmeter, ohmmeter and ammeter. You may well do it BEFORE you receive many (or even any!) lectures on electricity. It will serve to make concrete those ideas you learned at school, or give you a chance to pick up these ideas. Read these notes carefully before doing the experiment. If there are things that are unfamiliar, then ASK!! Ask your friends, lab partners, demonstrators, tutors, lecturers. You should make yourself familiar with the concepts of charge, current, potential difference and resistance. Measuring voltages and currents in simple circuits will give you an intuitive feel for these concepts. It is important to internalize these concepts by measuring simple physical systems. Just hearing a lecturer talk about them is not enough.

18.2 The Multimeter

The multimeter is a widely used instrument in science, technology and industry. The Goldstar DM-9183 is simple, accurate to three figures, and fairly robust. Still, do not drop it! They cost about R300 and if you break it you pay! You will be issued the multimeter in exchange for your registration card, which you get back at the end of the afternoon. No card, no experiment, no marks. Simple. So bring your card to the lab.

The multimeter is simple to use. You can best learn how to use it trying it out, measuring some voltages and resistances. For measuring the potential difference between two points, put one lead in COM, the other into VΩ, and connect the other ends of the leads to the points between which you want to measure the potential difference. Set the switch to an appropriate range (marked in white) for direct voltage measurement. This is marked by a V with a bar on top. The multimeter is now a voltmeter. This sounds complicated; it is easier to understand when you have the multimeter in front of you. If you are stuck, ask the demonstrator.

For measuring resistance between two points, put one lead in COM, the other into VΩ, and connect the other ends of the leads to the points between which you wish to measure the resistance. Set the switch to an appropriate range (marked in white) for resistance measurement. The multimeter is now an ohmmeter. For example the scale 200 will measure resistances up to 200 ohms.

For measuring the current in a wire, disconnect that wire. Connect one end to the mA input of the multimeter, and the other to the COM input. In this way the current flows through the multimeter. Set the switch to an appropriate range (marked in white) for direct current measurement, indicated by an $\bar{A}$. The multimeter is now an ammeter. *Note: Different current ranges require the leads to be plugged into different positions,* i.e. for 2 A range or less, plug the lead into the 2 A position, for 10 A range use the 10 A position.

18.3 The Experiment

The experiment is open ended. It consists of twelve parts. Some students may complete them all during the afternoon. Some will not. Progress as far as you can. Keep a CLEAR record of what you do in your lab book. For each stage draw the circuit you use in your lab book. Measure and record the voltages and currents as asked. State units. State your conclusions briefly and clearly. Make sure that YOU dont leave all the measurements to your partner. YOU must get experience in hooking up the circuits yourself. Answer the questions asked.

1) 1 battery. If you connect a wire directly across the poles of a battery a large current will flow. This is called a SHORT circuit. The battery will discharge (i.e go dead) quickly. Then you cannot do any more measurements. So don't do this. Also, connecting the multimeter across the poles of the battery when it is in ammeter mode will also cause a short circuit. Don't do this either. If you do, a new battery will cost you a rand.

Measure the voltage across the terminals of a battery. Does it depend on how well you make the connections? How sensitive is it?

2) 1 lightbulb. Use the multimeter to measure the resistance of the lightbulb. Does it matter which way round the multimeter leads are put?

3) 1 resistor. Use the multimeter to measure the resistance of the resistor.

4) 1 connecting wire. Use the multimeter to measure the resistance of a short piece of copper wire.

5) 1 battery, 1 lightbulb. Connect the battery and lightbulb to form a complete circuit. Measure the voltage difference across the battery. Measure the voltage difference across the lampbulb. Are these the same? If you change the polarity of the battery, do these values change? Does the brightness of the lightbulb change?

6) 1 battery, 1 resistor. Connect the battery to the resistor to form a complete circuit. Measure the voltage difference across the battery. Measure the voltage difference across the resistor. Are these the same? Measure the current flowing in the circuit by using the multimeter as an ammeter. Calculate the resistance of the resistor by dividing the voltage across it (in volts) by the current flowing through it (in amps). This gives the resistance in ohms. Disconnect the resistor from the battery and measure the resistance of the resistor by using the multimeter as an ohmmeter. Do you get the same value?

7) 1 battery, 1 lightbulb (again). Set up this circuit. From appropriate measurements on the circuit (you decide what to measure) calculate the resistance of the lightbulb. Disconnect the circuit and measure the resistance of the lightbulb using the multimeter. Do the results agree? If not, why not? Were the physical conditions of the lightbulb the same during the two measurements?

8) 1 battery, 2 lightbulbs (series). Connect the two lightbulbs in series with the battery, i.e in such a way that the same current flows through each lightbulb. Does the light bulb closer to the positive end of the battery burn brighter? Why not? Measure the voltage difference across the battery, and across each lightbulb. Is the sum of the voltage differences across the two lightbulbs the same as the voltage difference across the battery? Measure the current in the circuit at three points, namely coming out of the battery, between the two lightbulbs, and going into the battery. Record these carefully. Is it always the same? Is no electricity being used up? What IS being used up? (Something is, for if you left the circuit for long enough the battery would run down and the lightbulbs would go out.

9) 1 battery, 2 lightbulbs (parallel) Connect the two lightbulbs in parallel, and then connect them across the battery, i.e in such a way that the current flows out of the battery and then divides, some flowing through each light bulb, and then combines again, and flows back into the battery. Do the light bulbs burn equally brightly? Do they burn as brightly as when they were connected in series? Why? Measure the voltage difference across the battery, and across each lightbulb. Is the sum of the voltage differences across the two lightbulbs the same as the voltage difference across the battery? Measure the current in the circuit

at three points, namely coming out of the battery, and through each lightbulb. Record these carefully. Are these the same? Is the sum of the currents through the lightbulbs the same as the current flowing out of the battery?

10) **1 battery, 1 resistor, 1 lightbulb.** Predict whether the lightbulb will burn brighter if the light bulb is connected in series with the resistor, or in parallel. Write down your prediction. Only then try it and see. When connected in series, is the brightness of the lightbulb affected by whether the current flows first through the resistor, and then through the lightbulb, or the other way around?

11) **1 battery, 1 lightbulb, 2 resistors.** There are several ways you could connect these. All in series, all in parallel, the two resistors in parallel with each other, but in series with the lightbulb, and other ways. Which way makes the bulb burn the brightest? Which way gives a) the biggest current flowing out of the battery, and b) the biggest current flowing through the lightbulb? Now connect them all in series. Measure the voltage difference across each element of the circuit (battery, lightbulb, resistor) in turn. Do these voltage differences add to zero? Follow the circuit around, always in the same sense, say clockwise. Now do they add to zero? If they do not, consult a demonstrator. Maybe you got the sign of the voltage difference wrong, or perhaps you have measured the voltage difference the wrong way around.

12) **1 battery, 1 lightbulb, 3 resistors.** How can you connect all of these so that the lightbulb burns more brightly than it did in step 11, when only two resistors were used? Connect with all elements in series. Is tere any position for the lightbulb that makes it burn more brightly? Some people argue that the lightbulb closest to the battery should burn the brightest, since the current gets 'used up' as you go along the circuit. Is there any evidence for this effect? Connect with all elements in parallel. Is there any position that makes it burn more brightly?

Weight of jar ~~[illegible]~~ 209.3 g
jar + water 321.3 g

Experiment 19

Electrical Heating

References:

Giancoli (3rd Ed) 14-4, 18-6

Halliday, Resnick & Walker (4th Ed) 20-3, 28-7

19.1 Aim:

To determine the specific heat of water using electrical heating.

19.2 Introduction

When an electrical current passes through a resistor, electrical energy is converted into heat. If the current is I amps, for t seconds, with a voltage V across the resistor, the quantity of electrical energy converted into heat is given by:

$$E = VIt. \tag{19.1}$$

If the resistor is immersed in water (in a copper calorimeter) while the current passes through it, then the heat produced causes the temperature of the water (and the copper calorimeter) to rise. If no heat is lost to the surroundings the quantity of heat, Q, produced is related to the rise in temperature, ΔT, by the equation:

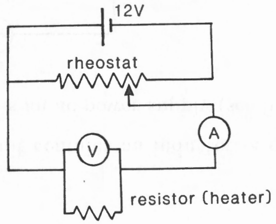
$$Q = (M_1 c_1 + m_2 c_2)\Delta T \tag{19.2}$$

where m_1 and c_1 are the mass and specific heat of the water; m_2 and c_2 are the mass and specific heat of the copper calorimeter.

19.3 Method:

Weigh the clean dry copper calorimeter on the triple beam balance. Fill it up to approximately 2/3 with water and weigh again. Connect the circuit as shown below:

Have the circuit checked by a demonstrator before switching on.



Place the heating coil in position in the calorimeter, making sure that the coil and the thermometer are completely immersed.

Switch on the 12 V supply, quickly adjust the rheostat to give a current of approximately 1.8 A, and switch off again.

Read the temperature of the water at intervals of 1 minute for about 5 minutes. Then switch on the supply and continue to take readings of the temperature, I and V at 1 minute intervals until the temperature has risen about 15- 20°C. Remember to stir well before each reading. Once the temperature has risen sufficiently, switch off the supply and continue to take readings of the temperature for about 10 more minutes. Plot a graph of temperature vs time in order to determine the temperature to which the water and calorimeter would have risen, had there been no loss of heat to the surroundings. (Use Newton's Law of Cooling as described in Exp.15.

Since all the electrical energy E is converted into heat, one can combine equations 19.1 and 19.2 to give:

$$VIt = (m_1c_1 + m_2c_2 + C)\Delta T \qquad (19.3)$$

where ΔT is the corrected rise in temperature;
C is the heat capacity of the stirrer and thermometer (approx 40 J K^{-1});
c_2 is the specific heat of copper (393 J kg^{-1} K^{-1});
V and I are average values of voltage and current during the heating cycle.

Solve Eq 19.3 for c_1, the specific heat of water. Make a rough estimate of the uncertainty in your value for the specific heat of water. (Since ΔT is likely to contain the greatest uncertainty, this is best done by first determining the % uncertainty in ΔT and then using this value to make an estimate of the error in c_1.)

Experiment 20

LCR Resonance

References:

Giancoli (3rd Ed) 21-13

Halliday, Resnick & Walker (4th Ed) 36-4

20.1 Aim

To investigate the response of a LCR series circuit to a sinusoidal voltage of a variable frequency.

20.2 Theory

As the name implies the LCR series circuit contains an inductor, a capacitor and a resistor which are connected in series across an ac power supply (see figure below).

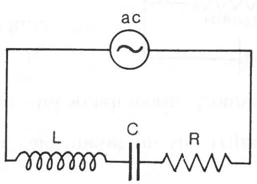


Figure 20-1

It can be shown (see lecture notes or any of above references) that the instantaneous current through the circuit is given by

$$I = I_o \sin(\omega t + \phi) \tag{20.1}$$

where

$I_o =$ current amplitude (peak current)

$\omega =$ angular frequency of ac power supply ($\omega = 2\pi f$)

$\phi =$ the difference in phase between the applied voltage and the current in the circuit. (Remember that the phase difference occurs because the voltage across L leads I by 90° and across C it lags I by 90° . The value of ϕ is given by the eqn: $\tan\phi = (\omega L - 1/\omega C)/R$).

Now the current amplitude I_o is related to voltage amplitude V_o of the applied voltage by

$$I_o = V_o/\sqrt{R^2 + (\omega L - 1/\omega C)^2}. \tag{20.2}$$

The magnitude of I_o therefore depends on the frequency of the applied voltage and it will therefore be a maximum when the condition $\omega L = 1/\omega C$ is met. A typical plot of I_o vs f is sketched in the figure below.

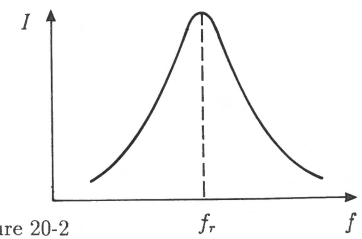


Figure 20-2

The frequency, f_r, at which the maximum occurs is called the "resonance frequency". Since $\omega^2 = 1/LC$ at "resonance" the resonance frequency is given by:

$$f_r = 1/(2\pi\sqrt{LC}). \tag{20.3}$$

20.3 Apparatus

You are supplied with a 220 Ω resistor, a 0.022 μF capacitor, a coil (inductor), a function generator and an oscilloscope. The function generator will be used to supply an ac voltage of variable frequency. The frequency of the ac signal may be read off the meter on the front panel of the function generator. The oscilloscope is used to measure the voltage, V_R, across the resistance and since the current through the resistor is directly proportional to V_R (i.e. $I_o = V_R/R$) the measurement of V_R allows one to determine the peak current I_o. (Of course the current is the same in magnitude and phase everywhere in the circuit and thus measurement of I_o through the resistor R determines it throughout the circuit.) The operation of the oscilloscope is discussed in considerable detail in appendix B.

20.4 Method

Connect up the circuit exactly as shown in the figure below. Interchanging the position of the L, C and R components will lead to one or other of the components being "shorted out". For the same reason you must ensure that the earth lead of the oscilloscope is attached to the earth side of the resistor R.

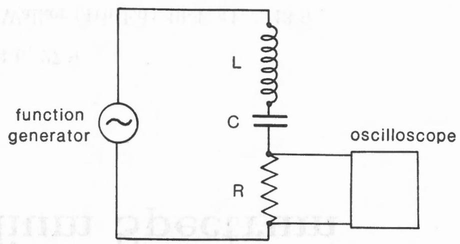


Figure 20-3

Set the output (waveform) of the function generator to sinusoidal and turn up the amplitude to its maximum position. Set the frequency of the signal generator to about 1 KHz and then establish the approximate position of the resonance frequency by sweeping the frequency (fairly rapidly) and observing the change in voltage on

the oscilloscope. Having established the approximate resonance frequency next decide the range of frequency over which you will take your measurements. Now turn the frequency down to the bottom of the range and begin to make accurate measurements of the function generator's frequency and the voltage across R. Increase the frequency slightly and remeasure V_R. Repeat this procedure until you have covered the frequency range you initially decided on. Make sure that you take sufficient readings in the vicinity of the resonance frequency. Plot a resonance curve of I_o vs f and determine the resonance frequency, f_r. Having obtained f_r calculate the inductance of the coil using Eq. 20.3.

Finally set the frequency of the signal generator to the resonance frequency and then check the reading on the frequency meter by using the oscilloscope (for measuring frequency with an oscilloscope see appendix B). Do your two values agree?

ADDENDUM FOR PHY104W

Physics 104W students will do some additional analysis of the resonance curve. To obtain a curve that is suitable for this analysis, the measurement procedure must be modified. At each frequency, measure V_R (the voltage across the resistor) **and** V_o (the applied voltage). Plot a graph of V_R/V_o against frequency. This ensures that the output impedance does not modify the shape of the resonance curve.

Determine the Q (quality factor) of the circuit from the relation $Q = f_R/\Delta f$ where Δf is the full width of the curve at (peak maximum)/$\sqrt{2}$.

Another value of Q can be obtained from $Q = 2\pi f_r L/R$. For L use the value previously calculated, and for R use the nominal value of the resistor. (The inductor will also have some resistance, but this should be much smaller than that of the resistor.)

Compare your values of Q.

3.8 div

50 ms =1 div

Experiment 21

The Sodium Spectrum

References:

Giancoli (3rd Ed) 24-6, 27-9

Halliday, Resnick \$ Walker (4th Ed) 40-4, 41-7, 43-9

21.1 Aim

To study the emission spectrum of atomic sodium using a diffraction grating.

21.2 Introduction

Sodium has an atomic number of eleven. The sodium atom may therefore be pictured to consist of a postively charged nucleus surrounded by eleven electrons. In terms of the Bohr model of electron orbits, and according to the Pauli Principle, each orbit may be occupied by no more than two electrons. Thus two of the eleven electrons will occupy the 1s orbital, another two the 2s and six the three 2p orbitals (thereby filling $n = 1$ and $n = 2$ shells completely), where 1, 2 refer to the principal quantum number n and s, p, refer to the angular momentum quantum number l=1, l=2 etc. When the sodium atom is in its ground state, the remaining electron will occupy the 3s orbital. However this electron can be relatively easily excited to one of the higher states and on de-exciting the electron will emit a photon whose wavelength λ is determined by the energies of the orbitals between which it is undergoing transition (i.e. $E_1 - E_2 = hc/\lambda$). The

energy level diagram of sodium, together with various allowed transitions are shown in Fig. 21.1.

We shall use a diffraction grating to study the sodium spectrum. With a grating, an intensity maximum (constructive interference) is only observed if the wavelength of the photon, λ, is related to the grating spacing, d, by the relationship:

$$n\lambda = d \sin \theta_n \tag{21.1}$$

Where n = order of the spectrum
θ_n = angle between zero and n^{th} order spectral lines.

Thus photons of a different wavelength (i.e. emitted by electrons undergoing transitions between different sets of levels) will satisfy the diffraction condition at different angles. The spectrum of the sodium will therefore be dispersed (spread out) by the diffraction grating and can be observed using a spectrometer.

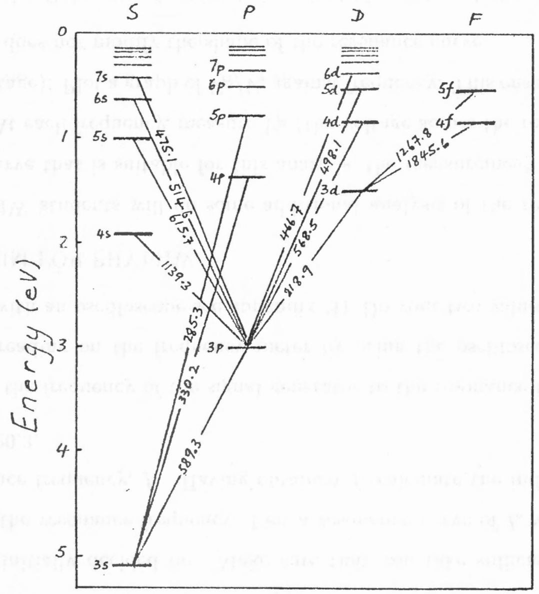


Fig 21-1. Energy level diagram of atomic sodium.

The horizontal lines indicate the energy levels of the orbitals in sodium. Also indicated

in the diagram are some of the allowed transitions together with the wavelength of the associated photon in nm.

21.3 Apparatus

Obtain a diffraction grating from a demonstrator and record its number in your record book. Refer to Experiment 5 and Appendix A for focussing and using the spectrometer.

21.4 Observing spectra produced by diffraction

Place the grating in the centre of the turntable of the spectrometer, perpendicular to the light beam from the collimator. Look through the telescope in the direction of the axis of the collimator: you should see a bright yellow line, which is the zero order "image" produced by the grating. Rotate the telescope slowly either to the left or to the right until you see the first order spectrum. Record the colours you see, in the correct order. Which colour is deviated the most? Does this agree with that predicted by Eq. 21.1?

Next check that the grating is perpendicular to the collimator. First return the telescope to the central image and set the crosswires on the fixed edge of the slit image. Read both verniers: the readings should differ by 180°. Turn the telescope to the right and record the position of the first order yellow doublet line. Then turn the telescope to the left of the zero order and measure the position of the other first order yellow doublet. By subtracting these readings from those of the central image you can find the angular separation of the two first order images. If these two differ by more than a few minutes of arc, the grating is not perpendicular to the light beam, and should be repositioned more carefully.

21.5 Measuring the grating spacing

In order to measure the wavelengths of spectral lines, one must first know the grating spacing. The gratings we shall be using in the laboratory have a spacing of about 3 μm. The exact spacing must be determined using the diffraction condition (Eq. 21.1) and the known wavelength of the yellow sodium doublet (589.3 nm).

Generally, both verniers of the spectrometer should be read for accuracy. However, for these measurements, you need read only one to save time. So choose one vernier and be sure to use it for all the readings.

Turning the telescope to the left, set the crosswires in turn on the yellow doublet line in each spectrum, for as many orders as you can see. Read the same vernier for each setting. Repeat these readings in reverse order, returning from highest to zero order, and take the average of the two readings for each order. Repeat the procedure while turning the telescope towards the right. By taking the difference between the "telescope left" and the "telescope right" readings for a given spectral order we obtain values for 2θ as shown in the Fig. 21.2 below.

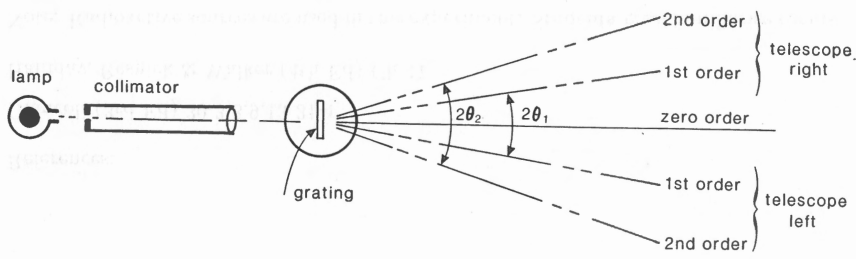


Fig 21-2

Find a value of $\sin\theta_n/n$ for each spectral order, and take a mean of these values. Hence calculate the grating spacing, d.

21.6 Measuring the wavelengths of the other spectral line

Having determined the grating spacing, we can now measure the wavelengths of other lines in the sodium spectrum. Select two of the other lines in the spectrum and check to see that the selected lines remain visible in the second and perhaps the third order spectrum. Follow exactly the same procedure as you did for measuring the position of the yellow line, except now use your measured value of *d* to find the wavelength of the selected lines. If you have time, repeat for other lines in the spectrum.

21.7 Identifying the transition

Having measured the wavelengths of various lines in the sodium spectrum your last task is to identify which transition was responsible for the lines of your choice. This can be done with the aid of Fig. 21.1. The yellow sodium line whose wavelength was given to be 589.3 nm is obviously a result of an electron transition between the 3p and 3s levels. Can your lines be unambiguously identified?

Experiment 22

Radioactivity and Shielding

References:

Giancoli (3rd Ed) 30-3,8,9,13 31-4

Halliday, Resnick & Walker (4th Ed) Ch 47

Note: Radioactive sources are used in this experiment. Students *must* familiarise themselves on the handling of radioactive sources by reading Appendix F before commencing with this experiment.

22.1 Aims

To use a Geiger counter radiation detector (a) to study the shielding properties of different materials for ^{60}Co gamma rays, and (b) to determine the linear absorption coefficient of lead for ^{60}Co gamma rays.

22.2 Introduction

22.2.1 Pre-prac Preparation

In preparation for this experiment you should consult your Physics text or some other reference book on nuclear physics and radioactivity. Make yourself familiar with such subjects as the properties of gamma rays and their interactions with matter, the detection of nuclear radiation in Geiger counters, the exponential absorption law for gamma

radiation and the estimation of radiation dose for gamma rays.

22.2.2 Apparatus

A measuring bench is provided (see Fig. 22-1), mounted on which are three stands, one to hold the Geiger counter, one to hold a radioactive source and the third to hold an absorber, or pack of absorbers, between the source and the counter. The Geiger is a fragile instrument and should be handled very gently. It should remain on its stand throughout the experiment. The Geiger tube (see Fig. 22-1) is connected by coaxial cable to an electronic unit which houses a power supply, an amplifier, a discriminator and a scaler. The scaler is a device which counts and displays the number of ionizing particles detected by the Geiger. The coaxial cable fulfils the dual purpose of carrying electric power from the electronic unit to the Geiger tube and carrying signals (pulses) back from the Geiger to the amplifier, discriminator and scaler. The scaler records the number of pulses occuring during a fixed counting period which may be preset to either 10, 20, 50, 100, 200 or 500 s.

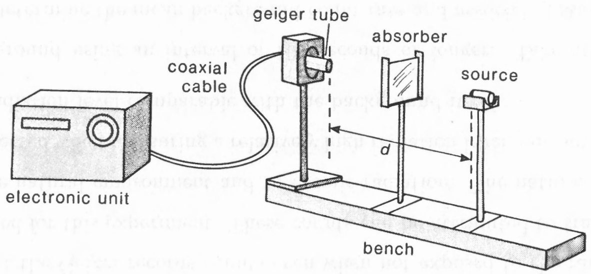


Figure 22-1

To complete the equipment required you must obtain a micrometer screwgauge and a radioactive cobalt source from your demonstrator (these will only be supplied in exchange for a registration card).

22.2.3 Precautions

Nuclear radiation can be harmful if proper care is not taken while working with it, so possible hazards should be taken into consideration in every situation in which it is used.

The sources which you will use in this experiment are relatively weak and are sealed in containers which prevent the escape of radioactive material while still allowing the gamma rays emitted by the ^{60}Co source to escape. The sources must be handled with care, and should not be handled unnecessarily. When not in use they should be placed in the lead shield provided and they should be returned to your demonstrator when no longer needed.

22.2.4 Setting up and handling the Geiger counter

The Geiger detector (see Fig. 22.2) has an axial anode rod surrounded by and separated from a coaxial outer tube or cathode. The tube is filled with a suitable counting gas, typically argon plus a trace of alcohol vapour at a pressure of about 1 atmosphere. One end of the tube is sealed by a metal window thin enough to allow the entry of beta particles (electrons) of energy approximately 0.1 MeV or greater. Atoms of the counting gas are ionised when electrons or other ionising particles enter through the end window or when gamma rays interact with the counter (usually in the outer tube) and eject energetic electrons into the gas. A voltage V is applied between the anode and cathode to sweep the ions and electrons rapidly to the cathode and anode respectively. A detectable electrical signal, called a count, is produced each time this happens, that is for each particle detected.

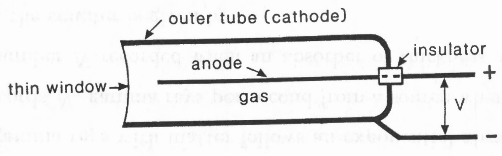


Figure 22-2

To set up the Geiger for operation the applied voltage V must be set high enough that all detectable counts are detected, but not so high that electrical breakdown occurs, since this will produce spurious counts. For the Geiger counters used in this laboratory an operating voltage of 420 V will satisfy these twin requirements. As the voltage tends to drift - especially during the warm up period - you should check the voltage from time to time during the experiment.

22.3 The natural background

You will notice that the Geiger records counts even when not exposed to the radioactive sources provided for this experiment. These counts can be attributed to traces of radioactivity in the natural environment and to cosmic radiation. The natural background can be neglected when measuring a relatively high radiation level, but not when measuring a low radiation level comparable with the background itself.

Measure the background using an interval of 100 seconds or longer. Take at least four readings and determine the mean background count rate and associated standard deviation (see section II.2).

22.4 Shielding of gamma radiation

You are required to compare the shielding of gamma rays by different materials in absorbers of equal thickness. For this you are provided with 10 mm thick slabs of aluminium, wood, iron, copper, perspex and lead. Determine the ratio of the count rates with the different absorbers to the count rate with no absorber. Hence calculate the fraction of gamma rays removed by each slab. Noting the densities (see below) and chemical compositions of the slabs, comment on your results.

Materials:	wood	perspex	Al	Fe	Cu	Pb
Density (g cm^{-3}):	0.70	1.20	2.70	7.80	8.90	11.30

22.5 The linear absorption coefficient of lead for ^{60}Co gamma rays

From your background reading (see section 22.2.1) you will be aware that the interaction of gamma rays with matter follows an exponential absorption law. If a Geiger counter records N_0 gamma rays per second from a source when no absorber is present then the number N recorded when an absorber of thickness x is placed between the source and the counter is given by:

$$N(x) = N_0 e^{-\alpha x} \tag{22.1}$$

where α is the linear absorption coefficient of the absorber material for the gamma rays emitted by the source. You are required to verify the exponential absorption law and to determine the linear absorption coefficient of lead for ^{60}Co gamma rays, which have a mean energy of 1.25 MeV. To do this you should leave the Geiger counter and source as set up for section 22.4. Remeasure the count rate obtained with no absorber in position and then successively with 1,2..6 lead absorbers, each of thickness about 3 mm, in position. Measure the thickness of each absorber before using it and note the total absorber thickness x used in each measurement. Make at least 4 measurements of N for each value of x. Use a time interval long enough to record at least 100 counts in each measurement. Determine the average count rate for each value of x, and correct for the natural background. Estimate a standard deviation for each corrected count rate.

Your results must be presented in the form of a graph (see Introduction, section II.1) which will be a straight line if Eq. 22.1 is valid. Determine the linear absorption coefficient α by fitting a straight line to your data and estimate the uncertainty in your value (see Introduction, section II.7).

EXERCISE

Suppose you wished to reduce, by a factor of 4, the radiation dose which you received from a ^{60}Co source at a distance of 0.5 m. You can do this either: (a) by stepping back; or (b) by inserting a lead shield between yourself and the source. How far must

you step back in (a) and what thickness of lead is required in (b)? Comment on the relative merits of the two methods.

Experiment 23

Half-Life

References:

Giancoli (3rd Ed) 29-8, 30-3,8,9,13

Halliday, Resnick & Walker (4th Ed) 47-3

This experiment is in the process of being revised. Once revised a new writeup will be made available to those students who are required to do the experiment.

Appendix A

Guidelines for the laboratory write-up

A.1 Headings should include:

1. Exp. no., title, date
2. **AIM**
3. **APPARATUS** – list, and record identifying letters or numbers.
4. **METHOD** – your own words. Keep it brief. Includes Theory. Must indicate how you are to achieve your aim.

not for short write-up

5. **RESULTS & CALCULATIONS** – Remember to **tabulate** your data - (see A2.) Include any graphs (see A.3) and calculation of result together with its uncertainty.
6. **CONCLUSIONS** – Summarize your results and discuss possible sources of error.

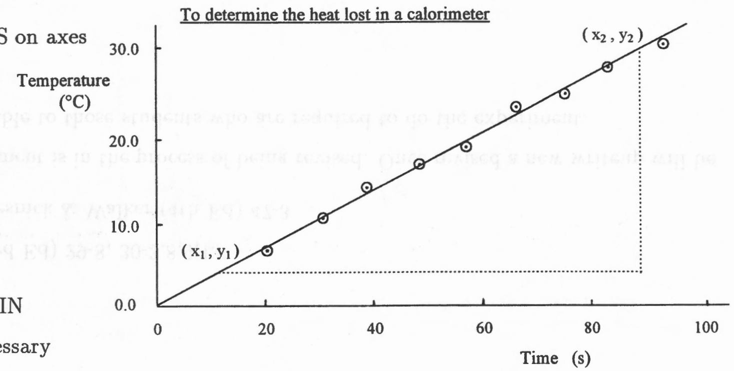
A.2 Tabulation:

1. TITLE: e.g. Table of readings of pressure and volume for an ideal gas.
2. HEADINGS:
3. UNITS
4. SPACE for the required number of readings

Pressure, P	Volume, V	$\frac{1}{V}$
mm. Hg.	cm^3	cm^{-3}

A.3 Graphs

1. TITLE: e.g. Graph of Temperature vs. Time for water in a calorimeter.
2. CHOOSE SCALES so that Graph fills the page.
3. LABEL AXES
4. UNITS on axes



5. ORIGIN if necessary
6. PLOT POINTS CAREFULLY: e.g. $\times$ $+$ $\odot$ $\square$ $\triangle$ NOT (a blob)
7. DRAW BEST-FIT STRAIGHT LINE to the plotted points.
8. SHOW CONSTRUCTION and CO-ORDINATES USED TO CALCULATE SLOPE choosing the points $(x_1, y_1), (x_2, y_2)$ far apart, and on the line.

$$\text{Slope} = \frac{y_2 - y_2}{x_2 - x_1}$$

Appendix B

Elementary Linear Measuring Instruments

B.1 The Vernier Callipers

B.1.1 The principle of the vernier

The vernier is a device by which the accuracy of a scale reading of a distance is increased. The simplest vernier is one divided into 10 equal division. The 10 vernier divisions equal 9 divisions on the main scale. The <u>least count</u> of the vernier is the smallest distance that can be read with the vernier. This distance is equal to the difference between a single main scale division and a single vernier division.

Example:

10 vernier divisions = 9 main scale divisions, so that if the main scale is a millimetre scale, then: 1 vernier division = 0.9 mm. The least count of the vernier is thus 1/10 $\times$ 1 mm = 0.1 mm.

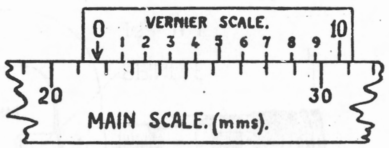


Fig. B-1

The reading of the above vernier is 21.7 mm. Note that the 7th vernier division coincides with a main scale division,

i.e. Number of main scale divisions + number of vernier divisions

$$21 \text{ mm} + (7 \times 0.1 \text{ mm}) = 21.7\text{mm}$$

B.1.2 Operating and reading the vernier callipers

This instrument is used to measure smallish objects accurately to 0.05 mm (e.g. length, diameter and depth) (Fig.B-2). First establish the least count. The instrument has a vernier scale as shown in Fig. B-3.

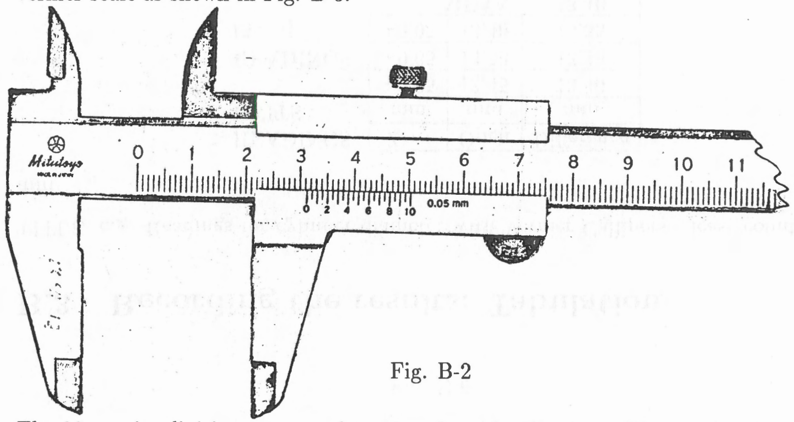


Fig. B-2

The 20 vernier-divisions are equal to 19 main scale- divisions. The vernier thus reads 0.00; 0.05 mm; etc...

Secondly take a "zero" reading with the jaws closed. Finally open the jaws placing the object to be measured firmly between the jaws and take the "open" reading. The result is the difference between the "open" and "zero" readings. Repeat this process 3 - 5 times. The magnified sketch (Fig. B-3) shows a reading = 2.175 cm.

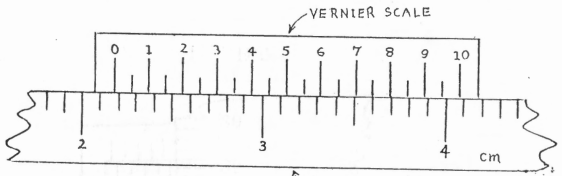


Fig. B-3

Tabulate the readings as shown in B-3.

B.2 The Micrometer Screwgauge

B.2.1 Description

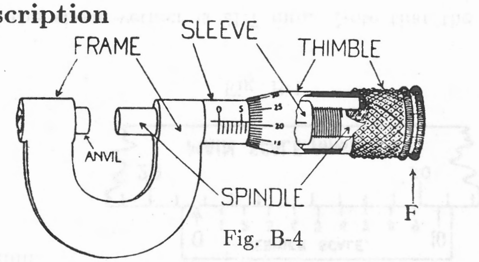


Fig. B-4

The instrument is used to measure accurately the dimensions of only small or thin objects. Basically it is a screw with an accurately constant pitch (the amount by which the thimble moves forward or backward for one complete revolution). The gauges in our laboratory have a pitch of 0.500 mm (two full turns are required to close the jaws by 1.00 mm). The rotating head or thimble is subdivided into 50 equal divisions. The spindle passes through a frame that carries a millimetre scale graduated to 0.5 mm. The jaws can be adjusted by rotating the spindle using the small knurled knob **F**. This includes a friction "clutch" which prevents too much tension being applied. The screw must be rotated through two revolutions to open the jaws 1 mm; in the process 100 divisions pass the reference mark on the sleeve.

B.2.2 Operating and reading the micrometer screwgauge

By examining the scales of the instrument establish the least count (the value in mm of 1 thimble scale division).

Next take a "zero" reading by rotating the spindle until it meets the anvil (i.e. closing the jaws). DO NOT SCREW THE SPINDLE TIGHTLY - THIS WILL DAMAGE THE THREAD.

Finally open the spindle and place the object between the spindle and anvil closing the spindle firmly but NOT TIGHTLY. Take the "open" reading, and subtract from it the zero reading to obtain the result. Repeat 3 - 5 times and tabulate as shown in B3.

e.g. When the reference edge is between 5.0 and 5.5 mm and division 24.0 on the thimble coincides with the scale on the sleeve, the reading is 5.240 mm (Fig. B- 5).

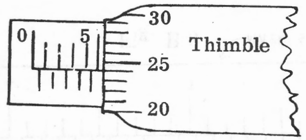


Fig. B-5

When the reference edge is between 5.5 and 6.0 mm and division 24.0 on the thimble coincides with the scale on the sleeve, the reading is 5.740 mm (Fig. B-6).

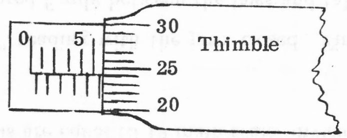


Fig. B-6

B.3 Recording the results: Tabulation

TITLE: e.g. Readings for cylinder diameter with Vernier Callipers - least count 0.02 mm.

HEADINGS:	Zero	Open	Difference
UNITS:	mm	mm	mm
	+0.05	13.45	13.40
READINGS	+0.05	13.50	13.45
(3 - 5)	+0.05	13.40	13.35
		MEAN	13.40

Appendix C

Focusing Microscopes and Telescopes

C.1 The Method of No Parallax

In geometrical optics we frequently need to locate and measure the position of an image or to adjust an optical system forming an image so that the image is located at a particular position such as the crosswires in the eyepiece of a telescope or microscope. For example, when a pin is viewed through a lens, we may see an image of the pin which is formed at a position different from that of the pin itself. The position of the object, or pin, is easy to measure, but how can we determine the position of its image? Additionally, in the case of a microscope or telescope, how can we ascertain that the position of the image which we observe coincides with the crosswires in the eyepiece? The method of no parallax provides a technique for achieving these objectives.

Parallax is defined as the apparent displacement of one body with respect to another when the position of the observer (not of the bodies) is changed. As an example, two pencils may be held at arm's length in line with one eye, but with one pencil a few centimetres behind the other. Hold one pencil point up, the other above and behind it with the point down. Without moving the pencils, move your head from side to side. Note that the pencils seem to move apart and together again as you move your head. However, as you bring the more distant pencil closer to you, the relative sideways movement of the pencils decreases. Eventually, when the two pencils are exactly the

same distance from your eye, moving your head does not cause a relative shift of the pencils. At this stage we say there is "no parallax" between the pencils and we can be confident that they are the same distance from the eye. The same technique can be used to set two images (whether real or virtual) at the same distance from the eye, or for that matter an image and a pin, or perhaps an image and a crosswire.

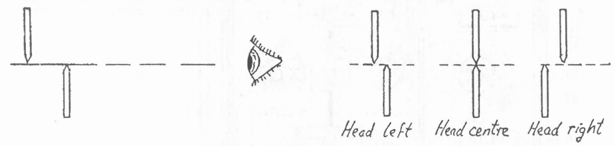


Figure C-1

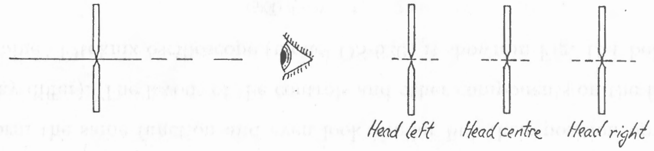


Figure C-2

C.2 Eyepieces of microscopes and telescopes

Eyepieces are focused first. Point the microscope or telescope at a well illuminated white piece of paper or sky. Start with the eyepiece screwed (or pushed) in as far as it will go, then move the eyepiece outwards until the crosswires become visible and sharp, and then become indistinct again. Relax your eye as much as possible and slowly move the eyepiece in again until the crosswires are perfectly sharp.

C.3 Focusing Microscopes

Firstly make sure that the microscope is upright. When viewing a particular object, rotate the wheel (height control) until a distinct image is formed. A fine adjustment should now be made until there is "no parallax" between the image and the crosswires.

C.4 Focusing Telescopes

Point the telescope through an open window (Louvre windows are provided on the Cape Flats side of the laboratory). Without disturbing the setting of the eyepiece, focus the telescope, i.e. move the objective lens relative to the crosswires, until some distant object (a kilometre or more away) is in sharp focus at the same time as the crosswires. This gives a rough setting only.

For a final setting, adjust the objective until there is no parallax between the crosswires and the image of the distant object. (New telescopes: reclamp the screw to prevent accidental sliding of the tubes.) The telescope is now "focused for parallel light", because only parallel rays will come to a focus exactly on the crosswires, and only an image exactly on the crosswires will have no parallax with respect to the crosswires when viewed through the eyepiece.

Appendix D

The Cathode Ray Oscilloscope

D.1 Description

Physically the main component assemblies are: the cathode ray tube, brightness and focussing controls, amplifiers for horizontal and vertical displacement of the trace and the time base unit.

Two types of dual beam oscilloscopes are used in the first year laboratory. Both are supplied by Elteknix and differ only in the layout of the controls (ie the knobs and switches perform the same function and even look similar but their position on the front panel may differ). The layout of the controls and other components on the front panel of the "blue" Elteknix oscilloscope (model OS-620) is shown in Fig. D-1 below.

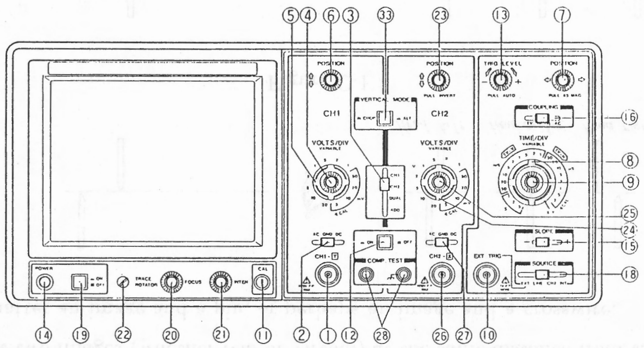


Figure D-1

Cathode Ray Tube. The essential parts of the cathode ray tube are shown in Fig. D-2. Electrons are emitted from the heated cathode, due to thermionic emission, and travel to the two anodes which control the intensity (or brightness) and focus of the spot produced by the electron beam on the fluorescent screen. After the anodes the electron beam passes through two sets of deflecting plates which deflect the beam in either of two orthogonal directions . The deflection is controlled by the voltages applied to the deflection plates. If the voltage applied to the plate is an alternating one, the beam will move back and forth across the screen, and the fluorescent spot will describe a **trace** on the screen characteristic of the form of the alternating voltage.

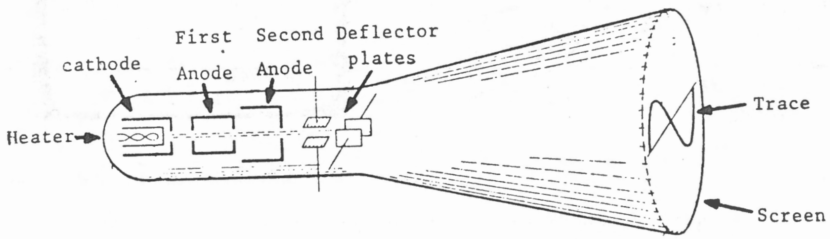


Figure D-2

Intensity and focus controls: The knobs which control the intensity of the signal and focus the beam are situated on the front panel (knob 20 and 14 in Fig D-1). These controls are rheostats which can vary the potential applied to the two anodes. Varying the first anode potential controls the number of electrons passing through this anode, and thus controls the **intensity** of the beam. The second anode acts like an electron lens, and varying the potential on this anode **focuses** the beam.

D.2 Vertical and Horizontal Amplifiers

Vertical amplifier: Since the incoming voltage signal applied to the vertical-input terminals (terminals 1 and 26 in Fig. D-1) is often small, the voltage applied to the vertical plates is increased using an amplifier. The amplification produced with this amplifier is calibrated according to the VOLTS / DIV setting (knobs 4/5 or 24/25,

depending on which channel is being used, in Fig. D-1). This calibration allows voltages to be determined from the corresponding vertical positions of the trace on the oscilloscope screen.

Horizontal amplifier: If no voltage is applied to the horizontal deflection plates of the cathode ray tube no horizontal displacement of the trace can occur. The time- base generator provides this deflection signal via the horizontal amplifier. The waveform is produced internally and has a "saw-tooth" shape (see Fig. D-3) which ensures that equal increments of time correspond to equal increments of horizontal displacement of the observed trace. Both horizontal and vertical displacements occur together reproducing the incoming waveform applied to the input terminals (1 or 26). An apparently stable pattern can be obtained by synchronizing the incoming and time base frequencies using the trigger level control (knob 13 in Fig. D-1). The observed waveform which corresponds to the signal applied to the input terminals is then built up as a repetition of overlapping traces.

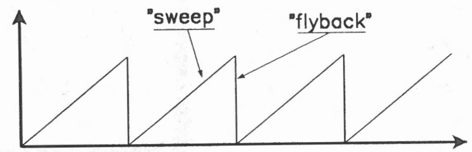


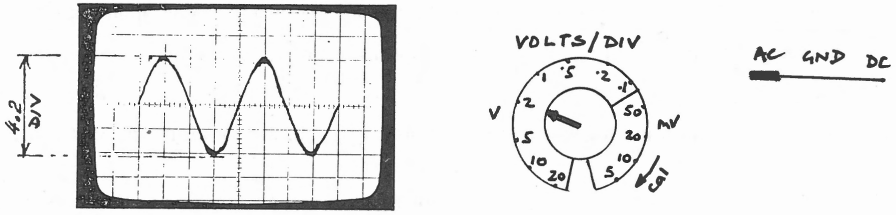
Figure D-3 "Saw-tooth" waveform

D.3 Time-Base Unit

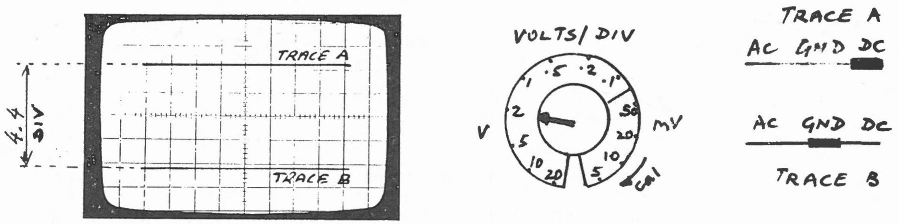
Horizontal sweep time selector: The sweep time-base unit is an oscillator producing the sawtooth waveform illustrated in Fig. D-3. The frequency is calibrated according to the SWEEP TIME / DIV setting (knob 8/9 in Fig. D-1). Therefore time intervals can be determined from corresponding horizontal positions of the trace on the oscilloscope screen.

D.4 AC and DC Voltage Measurement.

To measure **AC VOLTAGES** the vertical difference in height of relevant positions of the trace are converted to VOLTS using the setting on the VOLTS / DIV switch. (However before any measurement can be made the voltage-base must be set in the "calibrate" mode by rotating the inside "variable" knob, 4 or 25, fully clockwise until a click is heard.) For example, if the vertical separation is 4.2 divisions, and the calibration is 2 VOLTS / DIV then the corresponding peak-to-peak voltage is 8.4 VOLTS. (The rms or "effective" voltage is therefore $V_{rms} = \frac{1}{2}V_{p-to-p}/\sqrt{2}$.) The accuracy with which the oscilloscope is calibrated is ±5%.



To measure **DC VOLTAGES** the deflection of the trace is measured when the DC signal is applied to the input terminals.

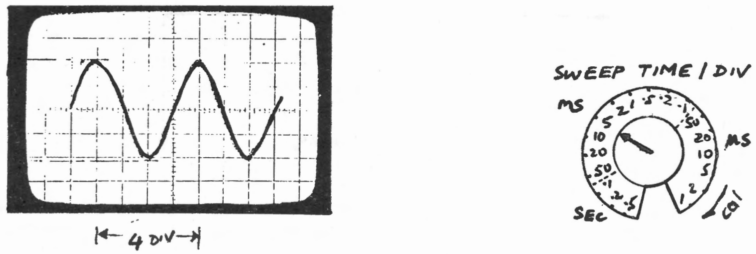


To obtain Trace B the input leads to the vertical-amplifier are connected together (zero volts input) or the AC-GND-DC switch (switch 2 in Fig. D-1) is set to the GND or ground position. Trace A corresponds to the deflection produced by the applied DC voltage (here assumed to be positive). For example, if the vertical position of traces B and A differ by 4.4 div, and the vertical-amplifier calibration setting is 2 VOLTS / DIV then the DC voltage applied is 8.8 VOLTS. The calibration accuracy is ±5%.

D.5 Frequency Measurement

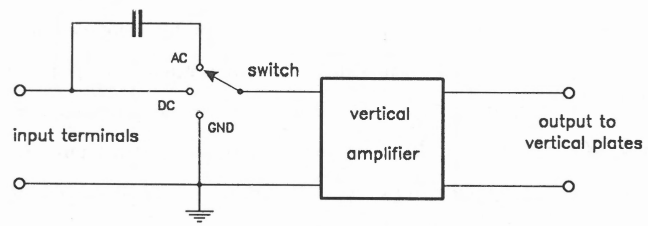
When the time-base is in the "calibrate" mode, frequency measurements can be made with the oscilloscope. For example, the trace of the AC signal shown below was obtained with the sweep time-base switched to 5 ms cm^{-1} scale. This means that the time taken for the spot to move 1 division horizontally across the screen is 5 ms. The wavelength of the signal shown is 4 divisions. Thus the period T of the signal is $5 \times 4 = 20$ ms and the frequency

$$f = 1/T = 1/20(\times 10^{-3}s) = 50\,Hz.$$



D.6 Other Function Switches and Controls

AC-GND-DC Switch:



With the switch in the "AC" position the input signal must pass through the capacitor C. Therefore only AC signals produce deflections of the trace on the cathode ray screen. With the switch in the "DC" position both DC and AC signals can deflect the trace.

Finally, with the switch in the GND position, the input terminals are shorted to ground.

To measure DC voltages the switch must of course be set in the "DC" position. When measuring AC voltages it is often useful to switch to the "AC" position. This prevents any vertical shift of the pattern as a whole when the sensitivity is changed. Indeed in some cases where the DC component is very large switching to the "AC" position is necessary if the trace is to be viewed at all.

Vertical position-shift: (knobs 6 and 23 in Fig. D-1) moves the datum position of the pattern vertically.

Horizontal position-shift: (knob 7 in Fig. D-1) moves the datum position of the pattern horizontally. Pulling this knob out results in the signal being magnified 5 times (horizontally) and therefore if the oscilloscope is being used to measure frequency this knob must be depressed.

Trigger slope: (switch 15 in Fig D-1) controls whether the sweep (trace) starts on the +ve or a -ve slope of the waveform. In the first year laboratory this is generally unimportant and can therefore be set to either position.

Trigger Level: (knob 13 in Fig D-1) determines the starting point of the sweep on the slope of the displayed waveform. This knob is used to prevent the waveform from rolling across the screen. Pull it out into the "auto" mode and if the waveform continues to roll rotate the knob until a stationary pattern is obtained.

Mode: (switch 3 in Fig D-1) determines which trace is displayed. If the test leads are connected to the input marked **X** then the signal will be displayed in channel **A** and the switch should be in position **CH A.** Similarly if input **Y** is being used the switch should be in position **CH B**. Of course if channel A is being used knobs/switches 2, 4, 5 & 6 control the display, while if channel B is being used 23, 24, 25 & 27 control the display. When switched to the **DUAL** position both traces are displayed and when in the **ADD** position the signal coming into input X is added to that coming into input Y and the sum of the two signals is displayed.

Other switches: these are not important for operation at the first year laboratory

level and they should be set in the following positions:

SYNC switch (16)	-	AC
SOURCE switch (18)	-	INT
COMP. TEST switch (12)	-	OFF

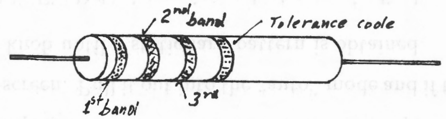
D.7 Quick set up check for the Oscilloscope

It is suggested, especially when unfamiliar with the oscilloscope, that the following procedure is followed in setting up the oscilloscope for use in the first year laboratory.

- Ensure that the power is switched on at the plug
- Set the three **POSITION** control knobs (6, 7, 23) to their mid-position and check that **PULL 5X MAG** knob is pushed in.
- Turn the **INTENSITY** control knob to mid-position
- Pull **TRIGGER LEVEL** (13) control to **AUTO**
- Check switches **16, 18 & 12** are in their correct position (see above).
- Decide which input is to be used and switch the **MODE** switch (3) to the appropriate position.
- Turn **POWER to ON**. If no trace appears after about 20 seconds adjust **INTENSITY** until it appears.
- Adjust **FOCUS and INTENSITY** controls until clear trace lines are obtained.
- Readjust vertical and horizontal **POSITION** controls for optimum viewing.
- Connect the test leads and adjust the time-base (8) and voltage-base (5 or 24) until a suitable display is obtained.

Appendix E

Colour Code for Electronic Components



0	Black
1	Brown
2	Red
3	Orange
4	Yellow
5	Green
6	Blue
7	Purple
8	Grey
9	White

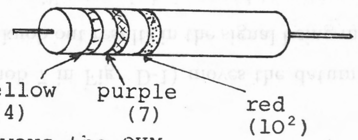
First band = First significant figure
2nd " = Second significant figure
3rd " = Multiplier, 10^x where x = number corresponding to its colour

or

3rd " = Number of noughts following the significant figures
4th " = Tolerance band: gold = ± 5%
silver = ± 10%

If no 4th band Tolerance is ± 20%

e.g. 4700 ohm =



Resistors - unit is always the OHM

Capacitors - unit is usually the picofarad = pF = 10^{-12}F
or microfarad = μF = 10^{-6} F.

Appendix F

Handling of Sealed Radioactive Sources

Some of the experiments in this course involve the use of radioactive sources. Radioactive sources must be handled like any other delicate pieces of apparatus. The source is issued in a form in which they are ready to use. **In particular, no attempt should be made to open a source.**

The sources have a low activity. However, it is best to minimise exposure by minimising the handling of the source, and by keeping a reasonable distance from the source at other times. If a source appears to be damaged in any way report this immediately to one of the demonstrators or the person in charge of the laboratory. Leave the area of the source.